JOURNAL OF

Petroleum Technology

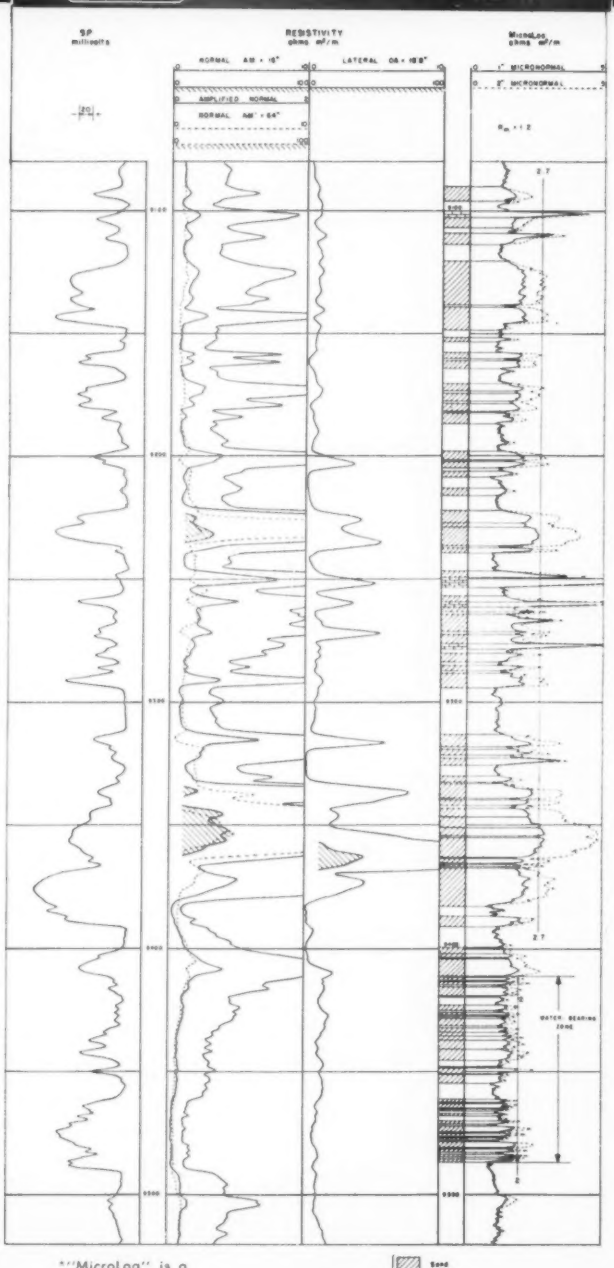
R. W. FRENCH

FEBRUARY, 1951

THE MICROLOG* IN UNCONSOLIDATED FORMATIONS

FRIO SAND
IN
POINT COUPEE PARISH
LOUISIANA

SCHLUMBERGER WELL SURVEYING CORPORATION
HOUSTON, TEXAS
Electrical Log



Mud (Caustic & Quebracho): R_m = 1.5 at B.H.T.
Bit Size: 9⅞"
Spacings: Regular — "MicroLog"
AM = 16" — Micronormal 1"
AM' = 64" — Micronormal 2"
AO = 18'8"

The "MicroLog" is a record of resistivity measurements made with electrodes at short distances from one another applied to the wall of the bore hole. The influence of the mud column is practically eliminated by an insulated electrode support.

The "MicroLog" was developed for use in consolidated formations. It has proven to be an equally valuable tool for investigating unconsolidated sections. It provides a remarkably detailed record of the formations, in particular, of permeable porous strata with reservoir possibilities. It then permits a very accurate determination of the amount of pay section.

Three formation types with precise boundaries are illustrated. The regular electrical log complements the "MicroLog" in analyzing the types:

1) Shale—Indicated by low "MicroLog" values with a minimum of separation between the curves. Thin shale or sand laminations are further characterized by breaks in the microcurve.
2) Unconsolidated sand — Indicated by somewhat higher (than shale) "MicroLog" values, usually with a separation between curves. The longer micronormal value is normally the higher on permeable, porous strata.
3) Consolidated (Calcareous) sand streaks—Indicated by high "MicroLog" values. Such streaks should be eliminated in determining net pay.

The amount of separation between the curves depends on certain characteristics of the media and on bore hole conditions. Compare the section from 9410' to 9480' with the rest of the log. Conditions affecting the separation include:

1) Amount of shale in the sand and/or thickness of the sand-shale laminations.
2) Salt water versus oil sand. The curve with the longer spacing will normally show a higher value in oil sand because residual oil is present in the invaded zone.

The "MicroLog" confirmed sufficient section in this case to attempt a completion from 9289-93'.

PRODUCTION RESULTS:

Perforated:	9289 - 93'
Potential:	147 B.O.P.D.
Gas/oil Ratio:	497 - 1
Water:	30%

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HOUSTON

*"MicroLog" is a Trade Mark of the Schlumberger Well Surveying Corp.

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Shale

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THE PROFESSIONAL MAGAZINE FOR PETROLEUM ENGINEERS

Journal of Petroleum Technology

Vol. III FEBRUARY, 1951 No. 2

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On the Cover — Richard W. French, whose picture may be seen on this month's cover, is Petroleum Branch, AIME, chairman for 1951. For a word picture of the new chairman, turn to Page 17, Section 1.

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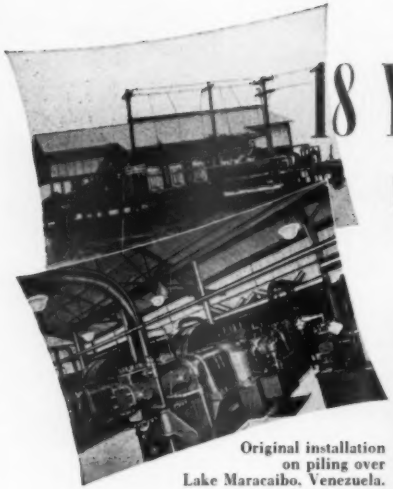

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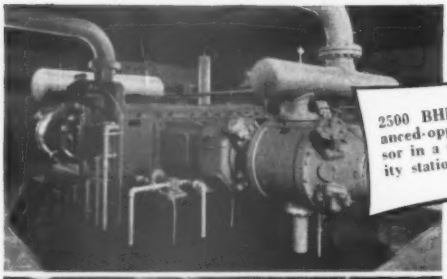
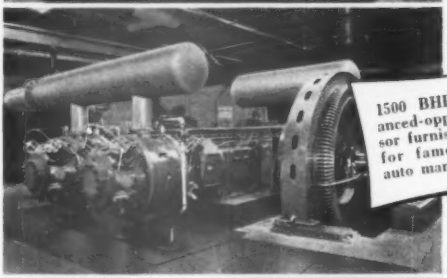
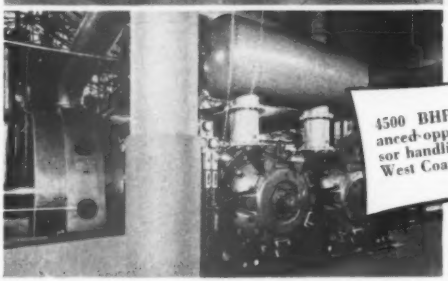


2500 BHP, 4 cyl. balanced-opposed compressor in a California utility station.



1500 BHP, 4 cyl. balanced-opposed compressor furnishing plant air for famous Michigan auto manufacturer.



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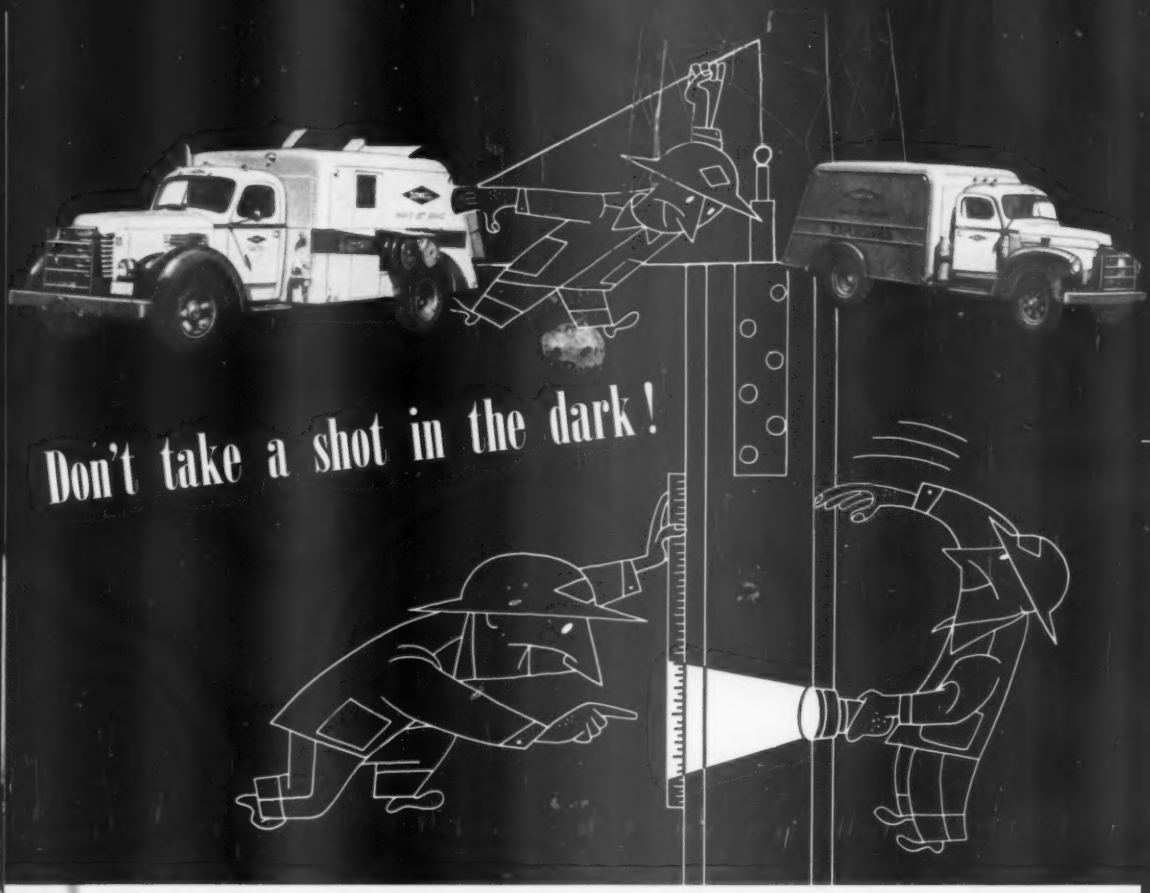

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Editorial Comment—

AT THE TURN OF THE YEAR

By John E. Sherborne
Union Oil Co. of California

The year 1950 has passed and it seems appropriate that at this time we pause to consider the events of the year just passed and to contemplate what lies ahead.

As is always the case, activities such as those carried on by a professional organization of the nature of the AIME require, for their successful prosecution, the diligent and wholehearted cooperation of many members. Recognition is due a number of persons — many more than can be recognized individually within these pages. An ever improving journal, the highly successful New Orleans and Los Angeles Meetings, the providing of all services previously available to members within a balanced Branch budget are items which bear testimony to the success of their efforts.

Highlights of the Past Year

Finances

Perhaps, in this era of deficit financing, the fact that the Petroleum Branch lived within its budget during 1950 is the most significant highlight of the year. The Branch enjoyed an income from all sources of $122,623.43 and incurred expenses amounting to $119,755.97 leaving a balance of $2,867.46. This surplus is being applied against a deficit in the Henry L. Daugherty Fund which accrued in previous years. Although this improvement results in part from the increased dues, and from a general tightening of all expenditures, a significant portion of it is the direct result of the excellent manner in which the editorial and business staff of JOURNAL OF PETROLEUM TECHNOLOGY has managed its publication during the year.

Journal of Petroleum Technology

As has been reported earlier, at the beginning of the year arrangements were made with the firm of McDonald-Thompson, publishers' representatives, to represent JOURNAL OF PETROLEUM TECHNOLOGY in the West and Southwest. The result of this firm's activities is beginning to show in the increased advertising obtained for the JOURNAL for 1951. More recently arrangements have been made for similar representation in the Eastern states. It is believed that advertising income will be over half again as much during 1951 as during the past year.

Also, the editorial policy has been broadened during the past year to provide a wider coverage of technical subjects than heretofore encompassed.

Technology Committee

In order to promote a wider variation of technical papers, steps were taken to broaden the important Production Technology Committee to a Technology Committee with sub-committees on Production, Drilling, and Natural Gas. This committee has the dual responsibility of providing the program for the annual meetings and of obtaining the technical material for the JOURNAL and Petroleum Transactions.

Membership

During 1950 Petroleum Branch membership increased from 3,502 to 3,928 paid-up members exclusive of student associates. With student associates included the total membership of the Petroleum Branch has increased to 4,969 members or 23 per cent of the Institute total. Of the new members who joined the Institute during 1950, 30 per cent were Petroleum Branch affiliates.

A new chapter at Casper, Wyo., and formation of a subsection of the Southwest Texas Section at San Antonio, Tex., are evidences of the continued growth of strength of the Petroleum Branch.

Board of Directors

Early in 1950 the procedure for nominating members for the Board of Directors of the Institute was modified to provide for redivision of the districts throughout the country such that each district would have the same number of members. Where possible, the arrangements of the districts were made in accordance with the professional interests of the membership. This procedure has been put into effect and board membership at present proportionally approximates professional membership.

General

As usual the annual meetings held last year at New Orleans and Los Angeles were highly successful. Local activities increased in pace with many splendid technical and social events. A new committee on Student Relations is attempting to establish closer liaison between members in industry and students by providing speakers and members in each school area to cooperate with Student Chapters. A special committee on organization and chapter financing has under consideration changes made desirable by the Branch system of organization.

However, much remains to be accomplished.

Problems Ahead of the Branch Leadership

Financing

Your leadership continues to work for dues proportional to service rendered on a Branch basis to the end that each Branch will pay its way. Continued vigilance must be exercised in decreasing the per member cost of services rendered.

Production Statistics

The publication of the Production Statistics continues to be a knotty problem. In spite of revised publication procedure, a charge for bound volumes, and continued support from the Henry L. Daugherty Fund, expenses attendant to the publication of this material exceeded income by about $5,000. Serious consideration is being given this matter, and it is hoped that a satisfactory solution to the problem can be reached at the St. Louis Meeting. ★ ★ ★

RECENT ADVANCES IN GAS LIFT EQUIPMENT AND TECHNIQUES

By Louis F. Davis, Member AIME, and Roy M. Willis
Atlantic Refining Co.

ALTHOUGH THE LIFTING OF DEEP LOW FLUID LEVEL WELLS IS STILL AN IMPORTANT PROBLEM TO THE PETROLEUM INDUSTRY, SOME GREAT STRIDES HAVE BEEN MADE SINCE 1948 IN THE EQUIPMENT AND TECHNIQUES USED. A REVIEW OF THESE ADVANCES IS MADE HERE.

DURING the past two years, important advances have been made in gas lift equipment and techniques. These have resulted in more efficient operation and have made possible the economical production of wells by gas lift at depths and rates not previously thought possible. The lifting of dual wells has been accomplished. Further improvements are in prospect that should increase efficiency and lower costs.

Due to the strict enforcement of regulations prohibiting the venting of gas, gas lift in the future will be almost entirely with compressed gas. This means an intensified demand for greater efficiency so that compressor investments can be reduced. More and more the gas lift industry is using engineering methods and thinking instead of the old trial and error system, and by engineering is maintaining its position in the artificial lift field.

During the early development of gas lift equipment and until the past two years, there was usually available a cheap supply of high pressure gas for the operation of the equipment in the areas where it was most widely used. After gas was used for lifting, it was ordinarily vented to the air. This situation no longer exists. Increasingly rigid enforcement of conservation regulations and the increase in the value of the gas is rapidly ending the era of cheap lift gas. Almost all future lift gas will be furnished by compressors, thereby greatly increasing the investment or price to the gas lift user. The amount of gas injected per bbl lifted directly determines the size of the machines needed, thus placing more emphasis on efficiency than ever before.

The lifting of deep low fluid level wells is an increasingly important industry-wide problem. The older forms of gas lift equipment could not do this efficiently, so drastic improvements had to be made. Dually completed wells were passing out of the flush stage, and requiring lift of one or both zones. So the stage was set for intensive development by these three factors: higher priced gas, deeper wells, and dual completions.

THEORY AND DESCRIPTION OF EQUIPMENT DEVELOPED

Large Port Valves

In 1948, intermittent lift by means of the bellows controlled valve had been in use for sometime. This valve had two outstanding deficiencies that had to be remedied if deeper wells were to be efficiently lifted. These were slippage and loss of pressure at the bottom of the hole due to the setting method used.

It was believed that slippage could be reduced by the injection of gas at higher rates. Observation of deep wells on intermittent lift showed a considerable amount of gas ahead of and in the liquid "slug." This gas contributed little to the lift process. In some cases where 2½-in. tubing was in use it was found impossible to work to the bottom of the well due to the "fall back," which was greater than the amount produced at the surface. It was theorized that the aeration of the slugs and the slippage was caused by the use of too low an injection rate, one that furnished insufficient energy for the high velocity necessary to maintain the "slug."

Accordingly, valves with larger inlet ports were designed and placed in field trial. The theories were confirmed, and solid slugs were obtained in 2-in. tubing from valves as low as 11,000 ft. There are indications that still larger ports are needed for 2½-in. tubing in extremely deep wells.

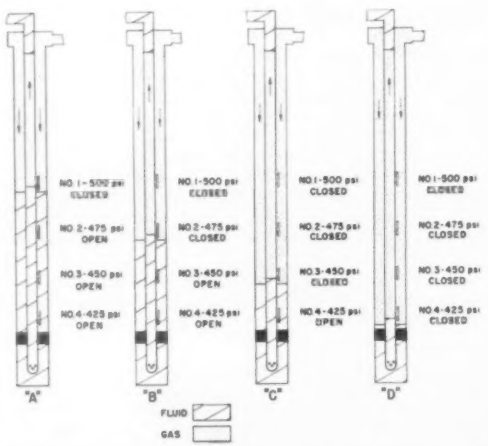

NO. 1 - 500 psi CLOSED
NO. 2 - 475 psi OPEN
NO. 3 - 450 psi OPEN
NO. 4 - 425 psi OPEN
"A"
NO. 1 - 500 psi CLOSED
NO. 2 - 475 psi CLOSED
NO. 3 - 450 psi OPEN
NO. 4 - 425 psi OPEN
"B"
NO. 1 - 500 psi CLOSED
NO. 2 - 475 psi CLOSED
NO. 3 - 450 psi CLOSED
NO. 4 - 425 psi OPEN
"C"
NO. 1 - 500 psi CLOSED
NO. 2 - 475 psi CLOSED
NO. 3 - 450 psi CLOSED
NO. 4 - 425 psi CLOSED
"D"
FLUID
GAS

FIG. 1 — INTERMITTER VALVE INSTALLATION WITH STEPPED-DOWN PRESSURE SETTINGS.

*Paper presented at the Petroleum Branch Fall Meeting in New Orleans, Oct. 4-6, 1950.

Methods of Setting and Operation

Fig. 1 shows the method of setting valves in common usage two years ago. Each valve was set at a pressure lower than the one above it, to prevent interference. The most popular drop between valves was 25 psi.

In a well 11,000 ft in depth, if the top valve were set for 700 psi, 12 valves would be required. By setting each valve at a pressure of 20 psi lower than the valve above, the bottom valve would have to be operated at 480 psi. By this type of valve setting, energy at the surface would be wasted that could be used at the bottom of the hole.

In almost every valve there exists a "spread" or difference between opening and closing pressures that is largely a function of the relationship between seat area and area of the power medium that controls valve movement. In Fig. 2 the effect of tubing back pressure on the valve spread is shown for a valve designed with a ratio of bellows area to seat area of 6 to 1. For a valve set to close at 500 psi, the spread varies as a straight line relation of back pressure from

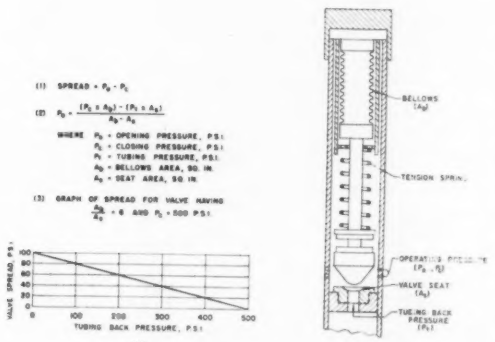


FIG. 2 — RELATION BETWEEN TUBING PRESSURE AND VALVE SPREAD.

100 psi spread with 0 psi back pressure to 0 psi spread with 500 psi back pressure, as shown in Fig. 2-A. The closing pressure of the valves remain constant at 500 psi. This relation of opening pressure and back pressure may be expressed as follows:

$$P_o = \frac{(P_c \times A_b) - (P_t \times A_s)}{A_b - A_s}$$

Where

P_o = Opening pressure of valve, psi
P_c = Closing pressure of valve, psi
P_t = Tubing back pressure, psi
A_b = Cross-sectional area of bellows, sq in.
A_s = Cross-sectional area of valve seat, sq in.

From Fig. 2-B, it may be seen that in opening the valve, the casing annulus pressure is exerted on the area of the bellows less the area of the valve seat, while the tubing back pressure is exerted on the valve seat area. Therefore, the valve opening pressure varies inversely with the tubing back pressure. The closing pressure of the valve remains constant since the valve closes with equalized operating pressure across the valve seat and bellows areas. Although the valve section in Fig. 2-B is shown with a tension spring to furnish the closing force on

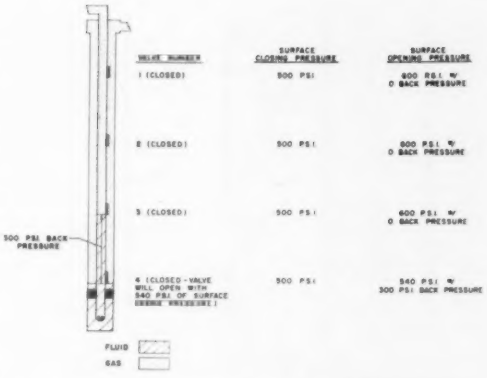


FIG. 3 — INTERMITTER VALVES SET AT SAME SURFACE PRESSURE.

the valve, this back pressure effect would be the same for pressure charged valves, neglecting the effect of temperature.

When the valve opens "dry" or against no back pressure, the spread is greatest, and when it is heavily loaded with fluid, the spread is least, due to the effect of the fluid load on the valve seat. Therefore, it was reasoned: Why not let the spread control the opening of the valves, and set them all at the same pressure? In all our discussion here, by pressure, unless otherwise designated, is meant surface operating pressure on the well space, usually the casing-tubing annulus, that operates the valves. The valve pressure is equal to the surface pressure plus the weight of the gas column from the valve to the surface.

Fig. 3 shows the operation of a string of valves all set to the same surface operating pressure. The unloading operation for this type of valve installation is basically the same as for the conventional valve installation shown in Fig. 1, with the exception that interference between the valves is prevented by the effect of tubing back pressure on the valve spread. All the valves below the fluid level are open. The valves above the fluid level are closed, since their opening pressures are higher by a figure equal to most of the spread with 0 psi tubing back pressure. When gas is injected at the well head, the lowest valve exposed to casing annulus gas will have the

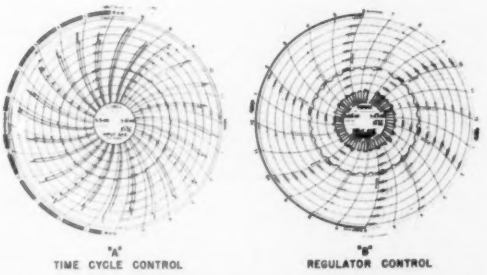


FIG. 4 — TYPICAL INJECTION GAS CHARTS FOR INTERMITTER VALVE OPERATION.

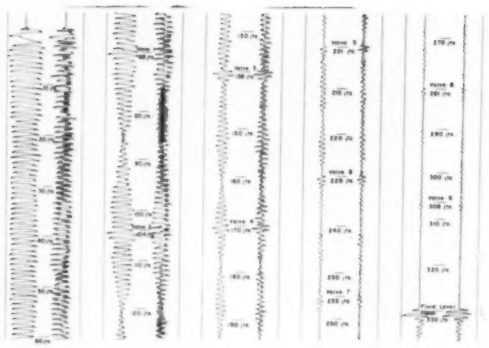


FIG. 5 — CHART OF SOUND REFLECTIONS IN TUBING-CASING ANNULUS OF GAS LIFT WELL.

greatest amount of tubing back pressure against it and therefore will have a lower opening pressure than any of the valves above. Because of this effect of tubing back pressure in lowering the opening pressure of the valve, operation of the lowest exposed valve will be assured without danger of opening the valves above. The surface pressure remains the same regardless of the valve operating depth. This type of installation with all valves set at the same surface operating pressure has considerable merit, since higher operating pressures are available at the operating valve. This permits utilization of surface gas energy that would normally be wasted in the conventional pressure step-down setting method shown in Fig. 1.

This type of valve installation also provides theoretically ideal operation when controlled on the surface by a pressure reducing regulator. In this method of operation, a choke is placed in the injection line between the regulator and the well head. The choke is sized to feed the casing annulus at a rate slower than the gas passage rate through the operating valve when open. With a string of valves all set to operate at 500 psi surface pressure, the regulator would be set to hold a constant casing annulus pressure of about 530 psi. This pressure will be maintained until fluid feed-in to the tubing creates sufficient back pressure to open the operating valve with 30 psi spread.

When the fluid build-up opens the valve, gas is injected under the fluid column delivering it to the surface. When the casing annulus pressure drops due to injection through the open valve, the regulator opens, allowing gas to be fed into the annulus through the surface choke at a rate slower than the gas passage through the valve. When the annulus gas pressure drops to 500 psi, the operating valve closes. The regulator at the surface continues to feed gas into the annulus until the casing pressure is raised again to 530 psi, at which time the regulator closes. The system is then "primed" for the next operating cycles, awaiting fluid fill-in to open the operating valve.

In Fig. 4, gas injection charts are shown for both the time cycle controller and the reducing regulator method of surface control. It may be seen from these charts that the regulator type of surface control makes high bottom hole gas injection rates possible without causing undue load on the surface gas system. Also, when using regulator control, gas is injected only when there is a head of fluid in the tubing. The input gas-oil ratio can be controlled by adjustment of the casing annulus pressure required to close the surface regulator. The higher the casing pressure is maintained above the valve

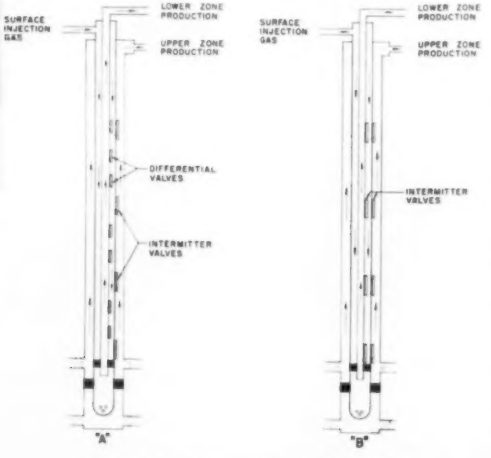


FIG. 6 — DUAL GAS LIFT INSTALLATION PLANS.

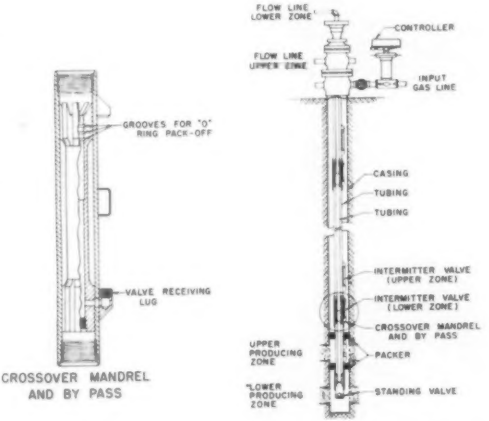


FIG. 7 — DUAL GAS LIFT INSTALLATION FLOWING BOTH ZONES THROUGH TUBING.

closing pressure, the smaller the fluid head required to open the operating valve. The smaller the build-up of casing pressure above the valve closing pressure, the larger the fluid head required to open the valve.

To permit successful use of regulator control on the surface, it is necessary that there be no leakage through any of the valves when closed. At present, this is the case with new valves only, and after some period of operation, valve leakage due to wear creates practical operating problems that make a return to time cycle operation necessary. It is hoped that future improvements in valve seats will make wholesale regulator operation possible.

Valve Testing

With intermitter valves set at the same surface operating pressure, it is not possible to tell which valve is operating. In solving this problem, the bottom valve is often set 25 psi lower than the rest. A rough approximation can be made by timing the interval from the opening of the valve until the head hits the surface, assuming a velocity of about 1,000 ft per minute.

The Sonolog or Echometer furnishes an ideal means of checking the operating fluid level. The casing can be shot without interfering with the operation of the valves or bleeding any gas from the casing. A typical chart of sound reflection in the tubing-casing annulus of a gas lift well is shown in Fig. 5. The location of all valves above the fluid level and

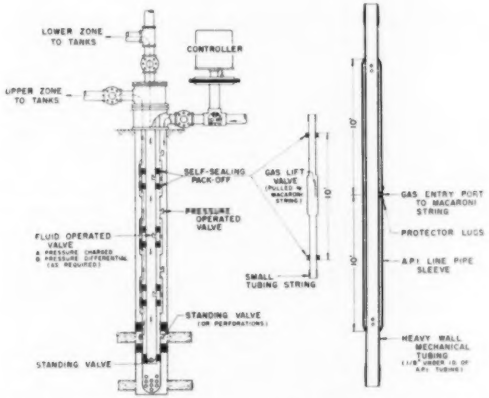


FIG. 8 — DUAL GAS LIFT INSTALLATION FLOWING BOTH ZONES THROUGH TUBING.

the operating fluid level are clearly discernible from the chart. The fluid level was located 330 joints from the surface at the bottom valve at a depth of 10,200 ft. Fifteen to 30 wells can be surveyed daily, depending on the suitability of well head connections to the use of a sonic device. In the past, testing to determine the operating fluid and operating valve in a gas lift well required the use of a bottom-hole pressure bomb which is both expensive and slow. Usually two to four hours are required to run a subsurface valve check with a pressure bomb.

Dual Lift

From the day dual completions were first used, the industry has posed the question of what to do when both zones cease to flow. Several solutions have been proposed which include the use of dual gas lift, dual rod pump, dual Kobe pump, dual Reda pumps, and abandoning one zone and lifting the other. Some work has been done on all types of dual lift with varying degrees of success. However, in this paper we will discuss the dual gas lift only. Figs. 6, 7 and 8 show some of the dual gas lift methods used.

Dual gas lift in shallow wells or high productivity wells is generally not too difficult since high frictional losses are seldom encountered. Dual gas lift in deep low productivity wells, however, often results in very high friction losses that seriously interfere with operations. These losses are caused by small diameter tubing, small clearances and other restrictions in the double strings of tubing required.

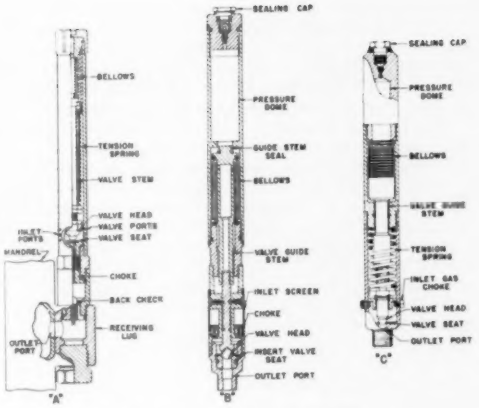


FIG. 9 — CONTINUOUS FLOW VALVES.

Fig. 6 shows the more common type of dual gas lift installations as used in the past two years. In each installation, gas is injected into the annulus between the two strings of tubing. Valves mounted on the larger tubing permit lifting of the upper pay through the casing-tubing annulus. Valves mounted on the smaller tubing permit gas lifting of the lower zone. In Fig. 6-A, differential valves are used for lifting the tubing phase and intermitter valves are used for lifting the casing phase. This type of installation is limited to use in high fluid level wells, with lifts of 4,000 ft or less, which is about the maximum practical operating depth using the differential type valve, unless extremely high injection pressures are maintained. In Fig. 6-B, intermitter valves are used for lifting both zones and, with proper selection of tubing sizes and careful attention to valve setting, can be used in deep wells. The efficiency of the casing zone lift is low, and valve life is shorter than normal. Installation costs are high, as special tubing must usually be used.

Figs. 7 and 8 show newly-developed dual lift plans in which the gas is injected into the casing-tubing annulus. The lower zone is produced through the small tubing string and the upper zone through the annulus space between the two strings of tubing. These plans eliminate the inefficient casing lift, but pose other problems of assembly and paraffin control.

Continuous Flow

The first form of gas lift was continuous flow using a gas injection pipe or flow pipe set below the working fluid level. From that beginning the science progressed through jet collars and automatic differential valves, both spring and weight loaded, to the modern continuous flow valves. These devices all operate on the same principle — aeration of the fluid column by continuous injection of gas in order to permit the energy of the expanding formation and injected gas to deliver fluid to the surface. Fig. 9 shows the various types of continuous flow valves.

The continuous flow valves, though similar in construction to the intermitter valves, operate as a back pressure controlled throttling type regulator. Gas injection rates through the valves are controlled by the use of small chokes. The valves are set at predetermined opening and closing pressures and are controlled by casing annulus pressure variations.

This type of installation permits very efficient lifting of wells having high bottom hole pressure and high fluid productivity where high fluid producing rates are desired. However, the continuous flow type of gas lift has obvious limitations. In order to maintain a reasonable injected gas-fluid ratio, the fluid column should not be lighter than about 0.15 psi per ft of depth for high per cent water cut fluid or 0.12 for low water cut fluid. In Fig. 10 is shown a pressure graph of a continuous flow installation where a producing rate of 1,728 bbl of fluid per day was obtained with input gas-fluid ratio of 240 to 1. Lowest point of gas injection was 3,518 ft using 735 psi of surface casing pressure.

It can be seen that the use of these valves is limited in depth by the available pressure and flowing gradient desired. This may be expressed as follows:

$$D = \frac{P - P_t}{G}$$

Where

D = Maximum operating depth in feet from surface.
P = Surface operating pressure of valve.
P_t = Flowing tubing pressure.
G = Average flowing fluid gradient.

This formula is a rough approximation, since the gradient changes with distance from the surface and the weight of the casing gas column is not considered.

Since gas pressures of over 900 psi are ordinarily not available for gas lift and gradients should be kept above 0.12 to 0.15, depending on the water cut, for most economical operation, few constant flow installations will be found lifting from below 4,500 ft. Their most valuable application is in heavy water producers with high fluid levels.

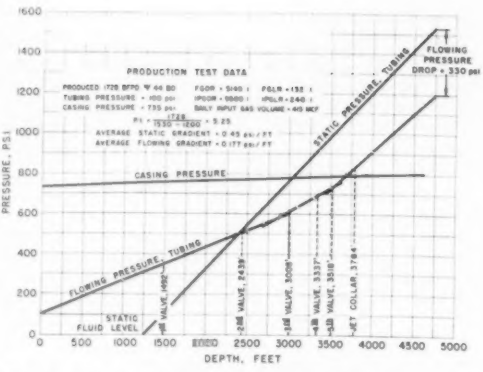


FIG. 10 — SUBSURFACE OPERATING PRESSURE DATA FOR CONTINUOUS FLOW VALVE INSTALLATION.

DEVELOPMENTS IN PROGRESS

Several developments are in prospect for the future, none of which should yet be considered complete.

Valves removable by wire line are now being manufactured. Under one plan only the bottom valve is removable. This type of design is suitable for low fluid level wells which can be unloaded to bottom by the conventional valves. The bottom valve, which takes most of the wear, is replaceable by wire line, thus reducing considerably the number of tubing jobs required. Under another plan all of the valves are removable individually so that any valve that is giving trouble or is worn out can be removed from the string withuot disturbing the others.

There is little doubt that these devices are mechanically feasible. Their use to date has been limited and whether they will be economical is still questionable. The hourly contract rates for wire line service are about 70 per cent of those for pulling units. The removal of valves by means of a wire line can become quite complicated and time consuming in deep wells. Also, the valves themselves are considerably more expensive than the conventional type. When these factors are all considered, it is doubtful if the use of removable valves in shallow wells will be economical. However, there are locations such as off-shore wells where these devices may enjoy considerable economical advantage.

Plunger lifts or "rabbits" are again being used. The design of the plunger has been changed so that special tubing is not required, thus reducing considerably the investment. The theory of the plunger is excellent and a successful plunger lift would give low ratios without the close attention to port sizes, pressures, head velocity, and head sizes that is now necessary. It should help control paraffin and permit the use of lower injection pressures, thus reducing the investment in compressors and high pressure fittings. On the other side of the ledger there will be the first cost and maintenance of the plunger and related equipment. There will be considerable wear and possibly difficulties with sticking plungers. Whether these costs and difficulties will offset the advantages of the plunger future use will have to show. It is believed that plungers will be successful and economical in light wells, especially those with high formation gas-oil ratios. They should also aid in the production of wells that make heavy emulsions which are aggravated by gas injection.

In summary, considerable improvement in gas lift equipment and techniques has been made during the last two years. Deep wells with low fluid levels are being efficiently lifted with large ported valves. New setting methods conserve operating pressure. Improved devices are available for testing operating levels. The development of dual lift equipment is progressing satisfactorily. Continuous flow methods have been improved. Better accumulation chambers are available.

Development continues at a rapid pace. New companies are being formed and competition is keen. The use of engineering thinking is now quite prevalent, and problems are attacked in a more scientific fashion as opposed to the hit-and-miss methods so often used in the past. The future holds new ideas and developments and it is believed that future changes will be as rapid and as radical as those that have been made in the last few years. With rising gas prices, gas lift must be kept increasingly efficient and economical in order to retain its place in the artificial lift picture.

ACKNOWLEDGMENT

The authors wish to acknowledge permission granted by The Atlantic Refining Co. to publish this paper. We also wish to acknowledge cooperation of the following firms in furnishing drawings of their equipment: Garrett Oil Tool, Inc., Camco, Inc., Merla Tool Corp., The Guiberson Corp., Wilson Supply Co., Bryan Gas Lift Equipment Co . ★ ★ ★

Technical Note 65——

A NEW TECHNIQUE FOR THE MEASUREMENT OF THE FORMATION FACTORS AND RESISTIVITY INDICES OF POROUS MEDIA

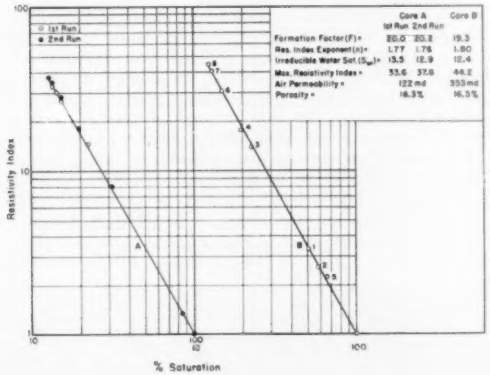
F. MORGAN, M. R. J. WYLLIE AND **P. F. FULTON,** GULF RESEARCH AND DEVELOPMENT CO., PITTSBURGH, PA., MEMBERS AIME

The importance of formation factor, F, not only in electric logging but as a fundamental rock parameter has recently been stressed.[1,2] The desirability of investigating the range of variation of the resistivity index exponent, n, in the relationship $I = S_w^{-n}$, where I is the resistivity index and S_w the water saturation as a fraction of the void volume of a porous medium, has also been urged.[2] The magnitude and variation of n with saturation and rock texture is a subject not only of theoretical interest but also one of prime importance in the interpretation of electric logs.

A simple technique has recently been developed which enables both F and n to be measured with high accuracy and which may also find acceptance as a convenient method for the determination of irreducible saturation attainment in the restored state method of core analysis.

Experience has taught that reproducible measurements of F are possible only if the resistance measuring electrodes are so arranged with respect to a plane face on a porous medium that they are able to make electrical contact with substantially all entry pores in that plane. In practice this may be achieved by using a platinized-platinum gauze electrode backed by some absorbent material (such as felt) which has been saturated with a fluid identical with that used to saturate the porous medium. Application of pressure to the electrode and absorbent material then forces the gauze against the plane face of the porous medium and simultaneously squeezes saline solution through the meshes of the gauze. By this means the electrode is in continuous aqueous contact with all pores and satisfactory and reproducible low resistance contact with the porous medium is achieved.

Clearly this method, although satisfactory for measurements of F, cannot be applied to the making of continuous resistance measurements on a porous medium while capillary pressure desaturation is being carried out. However, accepting the principle that for satisfactory results electrical contact must be made between a measuring electrode and all pores adjacent to that electrode, methods of bringing electrodes into intimate contact with the surfaces of porous media were investigated. Two methods were ultimately found to be satisfactory: in the one, the metal electrode is formed on the required portion of the porous medium by the use of a metal spray gun, while in the second the electrode is painted on with an ordinary camel's hair brush. The first method has the advantage of permitting the use of any metal which can be sprayed, but has the disadvantage of requiring rather elaborate and expensive equipment. The second method is presently limited to silver electrodes although in principle other metals, *e.g.* platinum or gold, could be used. Moreover, the method is so simple and cheap, and has been found to be so satisfactory that it will be described in some detail.



The core being investigated is cut into a right circular cylinder and is extracted and dried in the usual manner. The ends are then lightly painted with silver conducting paint* of the type used in printed electrical circuits. The quantity of paint used is not critical but the minimum compatible with entirely coating the core ends is recommended, particularly on the end that contacts the barrier. The core is then dried at atmospheric temperature for one hour or for shorter periods at any suitable elevated temperature up to about 110°C. It will be found that silver coatings so prepared are not only strongly adherent but also permeable and the core may be desaturated by the ordinary capillary pressure technique through one of the coated faces. The same permeability is characteristic also of thin metal coatings formed using the spray-gun technique.

An ordinary Lucite capillary pressure desaturation cell has been adapted to a form suitable for measuring the resistivity of the saturated silver faced cores both at 100 per cent saturation (*i.e.*, F) and at intermediate saturations down to the irreducible minimum. This has been achieved as follows:

A Coors porcelain barrier, having a displacement pressure of c 30 psi was grooved across a diameter. Dimensions of this groove were c 1 mm deep and 1 mm wide at the top. The groove was then painted thickly with silver conducting paint, the paint in the groove being extended lightly over the edges of the groove for a distance of c 1 mm on each side. A 30 gauge silver wire was then arranged in the groove in a form of a spring bow, each end of the silver being held at diametrically opposite ends of the groove by means of plastic cement. The arc of the bow at its highest point was arranged to be a millimeter or so above the face of the barrier, while one end of the bow wire was led by means of a pressure-tight connection through the wall of the capillary pressure cell. The groove in the barrier was then surrounded by suitably cut portions of Kleenex in the conventional manner so as to ensure capillary continuity from core to barrier, and the core placed on the barrier. The weight of the core distorted the silver spring bow and good electrical contact was thereby made between the outside of the cell and the lower painted silver electrode. Electrical connection to the top painted silver

*Type S.C. 11 provided by Microcircuits Co., New Buffalo, Mich., has been found to be very satisfactory.

electrode was made in the following manner. On the top electrode was placed a silver plated brass disc of 2 cms diameter and 2 mm thickness. The purpose of this disc was to obviate any corrosion effects resulting either from dissimilar metal contacts or from vapor condensed on the helical spring which was attached to the cap of the capillary pressure cell. This spring served the dual purpose of holding the core in contact with the barrier and silver wire, and making electrical contact with the silver plated disc and thus the top silver painted electrode.

Using this technique with cores 1.91 cm in diameter and approximately 2 cm in height and making use of a conventional 1,000 cycle conductivity bridge to measure resistance, results were reproducible within the accuracy of the resistivity measuring equipment and the saturation determinations. Saturations were determined gravimetrically, no serious difficulties in reproducing the resistance prior to removal being encountered when returning a core to the cell after a weight measurement. The maximum resistance discrepancy thus found has rarely exceeded 3 per cent and it is generally less than 2 per cent.

Two typical results are shown in the figure. In *A* the reproducibility is evident as is the fact that n is independent of saturation. In fact no case has been observed where n is saturation dependent, except at very low values of saturation where the core matrix resistance itself may be significant.[4] Curve *B* is of interest as a case where, because of barrier breakthrough and other difficulties, the core twice had to be removed from the cell, during which time it was immersed in brine and reimbibed fluid after being partially desaturated. The points are numbered to show the sequence of desaturations and resaturations. It will be observed that no hysteresis effects are apparent.

ACKNOWLEDGMENT

The authors are indebted to B. Greifer for a suggestion which led them to the choice of silver conducting paint. Their thanks are due to Paul D. Foote, executive vice-president, Gulf Research and Development Co., Pittsburgh, Pa., for permission to publish this note.

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Technical Note 66——

FLUID DISTRIBUTIONS CHARACTERIZING GAS-LIQUID FLOW

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It is the purpose of this note to call attention to the circumstance complicating the attainment of uniform gas-liquid distributions in multi-phase flow systems, and especially in those of the so-called Hassler type.[1] Although the complication arises directly as a consequence of gas compressibility and the dependence of fluid distributions on interfacial curvature phenomena, little reference to the problem has yet appeared in the literature.[2] In fact, it is only the paper of Geffen et al.[3] which gives any experimental evidence that a problem exists. On the other hand, previous authors[1,4,5] have made the tacit, albeit fallaceous assumption that uniform gas-liquid distributions automatically are established in linear flow systems by the expedient of maintaining the pressure gradients equal in the flowing gas and liquid phases. Such a device, it can be shown, will succeed only if the immiscible fluids are both equally compressible or both essentially non-compressible. Another necessary condition required before uniform fluid-fluid distributions can be achieved is that the porous matrix is isotropic.

Uniform fluid saturation distribution conditions obtain in isotropic media only when the curvature of each interface of contact between wetting and non-wetting fluids is everywhere the same throughout the interspaces. This is a necessary condition which follows from the consideration that variation in interfacial curvature gives rise to finite capillary pressure gradients and therefore to variation in the saturation distribution. That this is not a sufficient condition follows from the consideration that hysteric possibilities allow for different saturations even though the capillary pressure gradient is zero. In any event, it will be recalled that it is the intent in the Hassler scheme of relative permeability determination[1] to obtain initially (by the capillary pressure drainage or imbibition process) uniform conditions of fluid distribution in the core sample, and then to maintain this uniformity during mixture flow so that the resultant fluid mobilities which are calculated will refer to steady-state transfer under fixed conditions of uniform saturation. If the flowing fluids are incompressible, it is recognized that employment of the same value of the pressure gradient in each fluid will result in maintenance of the initially obtained condition of zero capillary pressure gradient. On the other hand, the consequence of gas compressibility is that the gradient in the gas pressure varies from point to point in the flowing stream, and since the pressure gradient in an incompressible liquid is constant it is thus impossible to maintain zero capillary pressure gradient during the simultaneous flow of gas-liquid mixtures. Therefore, one would expect to observe a variation in the gas-liquid saturation in the directions of the capillary pressure gradients, depending in magnitude on the particular way saturation changed with capillary pressure.

In order to formulate the manner gas compressibility effects prevent the attainment of uniform gas-liquid distributions during mixture flow, consider a linear flow system of unit length. As noted, it is necessary to assume an isotropic medium (*viz.* one where permeability is independent of position and direction). One then can arbitrarily set the pressure drops in the gas and liquid phases equal across the linear flow paths. Then the capillary pressure P_c at any point x where $0<x<1$), will be given by:

$$P_{c_{(x)}} = \left[P_{g_{(x=0)}}^2 - x \left\{ \left(P_{g_{(x=0)}} \right)^2 - \left(P_{g_{(x=1)}} \right)^2 \right\} \right]^{1/2} - \left[P_{L_{(x=0)}} - x \left\{ P_{L_{(x=0)}} - P_{L_{(x=1)}} \right\} \right] \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where P_g and P_L are the gas and liquid absolute pressures at the point $x=0$ or $x=1$. Implicit in Equation (1) is that the gas is the non-wetting phase and the liquid is the wetting phase. It is instructive to derive from Equation (1), then,

an expression for the maximum difference in capillary pressure which will obtain in the given linear gas-liquid flow system. This is:

$$\Delta P_{c_{max}} = \left[P_{c_{max}} - P_{c_{\substack{(x=1)\\(x=0)}}} \right] = \frac{\Delta P^2}{8\bar{P}} \quad . \quad . \quad . \quad (2)$$

where ΔP is the arbitrarily fixed pressure drop set equal in the flowing fluids, and $\bar{P}$ is the mean gas pressure. Thus, it is Equation (2) which when used in conjunction with the appropriate capillary pressure data shows the maximum variation in saturation distribution due to the finite capillary pressure gradients obtaining in gas-liquid flow systems of the Hassler type. Equation (2) also explains the statement of Geffen et al.[3] that "using differential pressures small compared to the absolute pressure" minimizes saturation gradients due to gas expansibility. The consequence of Equation (2) is that the effective permeabilities afforded by the uniform medium to the transfer of the non-wetting gas and the wetting liquid will vary with position, such that the laboratory data which are obtained will not measure true steady-state fluid mobilities under conditions of zero saturation gradient.

Equation (2) is an exact formulation, and as such it shows that employing small pressure drops and/or selecting large values of mean gas pressure both contribute to conditions of small capillary pressure gradients, as is desired in the laboratory study of relative permeability phenomena. In fact, these are the conditions which usually characterize reservoir flow processes, especially at points removed from the well face discontinuity. (N.B. Points in the reservoir close to the well face are characterized by the greatest pressure gradients and the smallest values for mean gas pressure.) Obviously, however, it is the variation of saturation with capillary pressure which is the determining factor, together with the maximum variation in capillary pressure along the flow path as expressed by Equation (2). For examples, a given value of $\Delta P_{c_{max}}$ calculated by Equation (2) can mean only negligible variation in saturation distribution if the wetting liquid is approaching its "irreducible" saturation, whereas it can result in appreciable saturation distribution variation when the gas saturation approaches its "equilibrium" value. This is because of the hyperbolic type variation between saturation and capillary pressure when the capillary pressure approximates the displacement pressure and small changes when maximum values of capillary pressure obtain.

It is concluded, therefore, that Equation (2) should be used in particular instances in conjunction with empirical data showing the variation of saturation with capillary pressure, in order to formulate the necessary conditions of pressure gradient and mean gas pressure which are required to give negligible saturation variations in gas-liquid flow systems. In this connection, it may be surmised from the nature of Equation (2) that previously reported gas-liquid mixture flow data have not been seriously in error except in the range of saturations where the gas relative permeability approaches zero. On the other hand, it will be recalled that the laboratory delineation of gas-oil ratio curves depends much on obtaining accurate relative permeability data in this saturation range.

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Richard W. French . . . 1951 Branch Chairman

Gracing the front cover of the JOURNAL OF PETROLEUM TECHNOLOGY this month is a picture of Richard W. French, the Petroleum Branch's 1951 Chairman. At about the time this issue is delivered, Dick will be picking up the reins of Branch leadership at the Annual Meeting in St. Louis from John E. Sherborne, retiring 1950 chairman. Thus, in more or less of a twinkle, the source of top Branch leadership will switch geographically from Whittier, Calif., to Cleveland, Ohio.

Although Dick's background was outlined on these pages a year ago when he became vice-chairman of the Branch, it will not necessarily be redundant to repeat the highlights of his life for purposes of reintroduction. Events from birth to present took him from Colorado Springs, Colo., to California, to Delaware, back to California, to Texas (for training with the old Air Corps), back to California, to Oklahoma, to Ohio. All of this resulted in his being designated vice-president of Production Operations for Sohio Petroleum Co., the position he now occupies.

Since graduation from the University of Delaware (third step in the series above) where he received a bachelor's degree in mechanical engineering in 1929, he has returned now and again to the educational waterhole for refreshers and for supplementary courses in such things as business administration, advanced engineering, advanced management (at Harvard) and graduate engineering work at the University of California. Dick explains this thirst simply: "I guess I'll never be educated."

That his contemporaries think otherwise is exemplified in his holding the high position he occupies with Sohio and in his being elected by the nation's leading petroleum engineers to guide their professional society's activities. As most men of position often do, Dick has done his share of menial tasks during the course of his career. Among these activities are included the operation of a hand shovel for Continental Oil Co. back in 1933. There followed for three years long hours as roustabout, pumper, gang pusher, compressor plant oiler, gas dispatcher, meterman and compressor plant operator. Reward came during the next seven years (1936-43) when he was made production engineer directing all of Continental's petroleum and production engineering in California. During this time he was contributing frequently to the AIME literature.

The years following found him assistant manager of Continental's production department in Ponca City, Okla. (seventh step above), chief engineer for Sohio and into his present position in Cleveland.

Free Gas Saturation and Water Flood Recoveries

By John Clayton Jacobs, Jr.
North Texas Section

C. R. Holmgren, of Stanolind Oil and Gas Co., and E. H. Robie, AIME Executive Secretary, spoke last month before the regular meeting of the North Texas Section in Dallas before an attendance of some 80 members.

Holmgren began by referring to the growing literature which indicates that the presence of free gas significantly affects the oil recoveries obtainable by water flooding. A number of reasons have been given for this effect, and Holmgren gave another — that the difference in residual oil content are due to simple displacement (*i.e.* the free gas occupies space which would otherwise be occupied by oil. He then described a series of experiments conducted on an Oklahoma sandstone core with the specific objective of isolating the effects of a static gas phase on water flooding recovery as differentiated from any alteration in the displacement mechanism occasioned by the presence of mobile gas.

Since Holmgren's talk was based on his paper, "Effect of Free Gas Saturation on Oil Recovery by Water Flooding," which was given at the 1950 Branch Fall Meeting in New Orleans and which is soon to be published in PETROLEUM TECHNOLOGY, a discussion of the experimental technique was omitted. The laboratory results indicated that the residual oil, at given water-oil ratio, could be reduced from the magnitude of 35 per cent to the order of 20 per cent. The residual oil in any given case was a function of the amount of free gas maintained in the sandstone core during the flooding experiments. And it was shown that the experimentally determined values for the reduction in residual oil content resulting from the presence of free gas can be duplicated by the use of ordinary reservoir calculating procedures based on the assumption that the effect of free gas is simply displacement of residual oil. Such calculations must, of course, take into account the reduced relative permeability to oil resulting from the presence of free gas.

Holmgren then turned to the practical application of the "free gas" technique. The "free gas" procedure potentially means a doubling of the water flooding recovery from many fields. Other advantages are the reduction in the amount of water needed for fill-up, and a more uniform oil producing rate. Limitations on the use of the method include a probable 10 to 1 reduction in the relative permeability to oil in the reservoir, with a concommitant reduction in the productivity indices of the wells. It might not be economical in some cases to operate at such lower producing rates. In some cases it would be desirable to produce the "free gas" by pressure reduction in the reservoir prior to flooding. Whether this procedure would be feasible in a primary water drive field would depend upon such factors as:

1. The shrinkage of oil, resulting from pressure reduction necessary to obtain the gas saturation, compared to the expected decrease in ultimate oil saturation.

2. Marked decreases in productivity indices of producing wells and hence an increased tendency for water coning.

3. Variation in oil properties with structure. Some high relief reservoirs have much lower bubble point oil at the water-oil contact than further up structure. Under such conditions it would be almost impossible to obtain free gas at the water-oil contact without depletion by internal gas drive of the upstructure part of the field.

Secretary Robie, making a tour of the Petroleum Branch local sections, described the Institute from the point of view of the New York staff. The big problem is budgetary, and all Institute activities are conducted on an economy basis. The history of the separate Branch publications is encouraging. The recent increase in dues makes it easier to balance our budget, and the increase was shown to be small in comparison to that charged in other engineering societies and with the long term national inflation. The Institute, in missing no bets to solve the financial problem, realized a nice profit from the promotion and sale of the volume *De Re Metallica*. Robie made the important disclosure that, despite these monetary difficulties, the Institute had, as a matter of principle, discontinued some 300 subscriptions to its publications which were subscribed by persons in the USSR and "iron curtain" countries. ★

1951 KANSAS SECTION OFFICERS are, L to R, front row, J. C. Gallivan of J. A. Terteling and Sons, vice-chairman for Western Kansas; L. D. Holsapple of Sinclair Oil and Gas Co., vice-chairman for Eastern Kansas; and G. L. Yates of Amstutz and Yates, chairman. Back row, L to R, are G. J. Decker, Schlumberger Well Surveying Corp., secretary-treasurer; and Tom Hamilton, National Cooperative Refinery Association, vice-chairman for Wichita.

Robie Outlines AIME Finances

By J. E. Kastrop
Southwest Texas Section

Installation of new officers, a visit by the Institute Secretary, E. H. Robie, accompanied by Joe B. Alford, Petroleum Branch Secretary, plus a regular technical paper presentation and a technical motion picture provided a full program for the January meeting of the Gulf Coast Section.

A. W. Waddill, vice-president of Houston Oil Field Material Co., was elected 1951 chairman; George R. Gray, Baroid Sales Division, National Lead Co., vice-chairman; E. F. Stratton, Schlumberger Well Surveying Corp., secretary-treasurer; George Fancher, vice-chairman from the University of Texas; and A. B. Stevens, vice-chairman from Texas A&M College.

Newly elected directors are: Herman Otto, Tennessee Gas Transmission Corp., Tom Borland, Stanolind Oil and Gas Co., and the past chairman, E. L. Petree, Gulf Oil Corp. E. B. Miller, Tide Water Associated Oil Co., and E. A. Rassinier, Phillips Petroleum Co., are holdover directors from 1950.

Outgoing officers and committee chairmen and members of each committee were acknowledged and thanked by Petree as he turned over the helm of the Gulf Coast Section to Waddill.

Joe B. Alford presented a complete financial report on the Petroleum Branch covering 1950 activities. According to his report, the Petroleum Branch was operating under its budget. He then introduced E. H. Robie, Secretary of AIME. Robie expressed his satisfaction upon visiting the local sections, and that it gave the members a chance to see the national officers. He briefly reviewed the background of AIME and explained how petroleum engineers became a part of the Institute. Founded 80 years ago by a small group of coal miners in Pennsylvania, metals and metallurgy was added in 1918. At the beginning of the oil industry, mining engineers became active in petroleum, and in 1922, the Petroleum Division was formed. Now, about one-quarter of the total Institute membership is composed of petroleum members. Total AIME membership is now about 17,000, with 4,500 student associates.

Robie went into the financial history, and told how the Johnson Committee was formed. It was this committee, Robie said, that recommended the division of the Institute into three divisions . . . Mining, Metals and Petroleum. It also recommended decentralization of administration, and suggested the formation of the Council of Section Delegates. They presented means for increasing Institute income, one such means was that of increasing dues. In order to go back to the old dues rate at the end of the three-year period, the Institute must increase its advertising in the various journals. In 1950, the income from advertising amounted to $104,000, compared to $86,000 in 1949. In order to increase advertising, we must increase our circulation, he said. This circulation can be increased by stepping up our membership drives.

Principal speaker at the technical session was Albert Trube, reservoir engineer, Tide Water Associated Oil Co., Houston. Trube was introduced by E. B. Miller, who said that Trube had been with Tide Water for the past eight years. Prior to that time he was with the Texas Railroad Commission, which he joined shortly after graduation from the University of Texas in 1936 with a degree in petroleum engineering. Trube spoke on "Pressure Maintenance in the New Hope Field," which paper he presented at the San Antonio meeting in

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E. H. ROBIE

When to Move In a Workover Rig

By Harry Vaughan
Gulf Coast Section

Henry N. Lyle, consulting engineer and formerly division engineer for Seaboard Oil Co. of Delaware, spoke to members of the Southwest Texas Section last month on "Before You Move in a Workover Rig."

Lyle said that even under favorable conditions, the success of a workover operation is not assured and the profit to be derived from it is problematical. Therefore, a prudent operator will examine carefully all the engineering and geological data available in order to assure himself that the objective of his workover has probability of attainment at a cost that will allow profit on the new production.

When workovers are not successful after a reasonably diligent effort, a review of the data on the reservoir may give some enlightenment as to the reasons for lack of success and may indicate that continued expenditures are not justified. Six examples of typical jobs in the Southwest Texas Frio Trend were used to illustrate the effect of sand thickness, structural location, proximity to faults, electric log interpretation, and errors in depth measurement.

The first meeting of 1951 for the Section brought out 168 members and guests to hear Lyle speak. New officers of the Section who will serve during 1951 were installed. They are Lee J. Thronson, chairman; George W. Wilson, vice-chairman; Harry D. Vaughan, secretary-treasurer; and directors J. M. Clark, Francis Hebert, Frank Saye, Chester Wheless, Barrett Booth, C. W. Kelley, Jr., Henry Kerr, Carl Peters and R. C. Granberry, Jr.

The new officers pledged to bring to the section an outstanding paper for each meeting during the year and increase the national and local membership columns. ★ ★ ★

Heavy Industry and Oil Fields of Europe

By W. G. Paul, Jr.
Pacific Junior Group

Fritz Huntsinger, who heads the Ventura Tool Co. of Ventura, Calif., recently completed a tour of Europe and brought back with him some vivid accounts of the activities of the petroleum and other industries as they are carried on under present conditions there. Speaking to members of the Junior Group of the Pacific Petroleum Chapter in Downey, Calif., last month, Huntsinger generalized in the following manner.

What started out as a pleasure trip to visit relatives and his boyhood home rapidly became a business tour of industrial and oil field installations. Through his brother-in-law, who manages a Swiss plant of 4,200 employees, Huntsinger gained access to industries in Switzerland, France, Italy, Holland, Belgium, Luxembourg and the East and West occupation zones of Germany. While this was his first visit to Europe since he came to the United States from Switzerland 28 years ago, Huntsinger was in better position to evaluate European industry than the average American, due to the entrees provided by his family.

While in Switzerland, he visited several plants engaged in the Fine Mechanics Industry, for which the Swiss are famous. He was particularly impressed by the electric power system which the Swiss have created. All new telephone and high power lines are carried in underground conduit. High tension lines up to 150,000 volts have been buried in this fashion. One power plant supplying this transmission system was described by Huntsinger. Generating equipment is located in a cavern blasted from solid granite 285 ft long by 90 ft wide by 84 ft high. Two penstocks drilled and tunneled through the mountain tap lakes at 10,000 ft elevation to supply the 160,000 kilowatt plant. From the exterior nothing is visible but a door in the cliff face. Protection against air attack was the primary reason for the plant's construction and the underground transmission lines.

From Switzerland, Huntsinger travelled through Holland to the German city of Celle which he described as the oil center of North Germany. He had planned to devote three days to a tour of the area, but due to the insistence of oil operators, he remained three weeks. Their feeling is apparently that an American can wave some magic wand and solve all their problems. They were insistent that Huntsinger visit each of their operations and make such suggestions as he saw fit. Their general problem is that they lag very far behind the United States in methods and equipment. Considerable problems were being experienced with twist offs which Huntsinger declared were due to low grade drill pipe and improperly designed tool joints. While some Hughes and Reed joints were beginning to appear, the Germans still cannot manufacture high grade drill pipe and are limited to grade D specifications.

Huntsinger was impressed, however, with the volume of drilling activity. Some 138 drilling rigs were in operation in Germany at the time of his visit. Many of these were operated by American oil companies including Gulf Oil Co., The Texas Co., Standard of California, Socony Vacuum and Shell Oil Co. Production is shallow, usually between 3,000 and 4,500 ft. Huntsinger noted, however, that quite a little American equipment is now beginning to appear in European operations.

While still in Celle, Huntsinger toured the plant of Salzgitter, the largest oil tool manufacturing company in Germany. He was impressed by their research program and their many new developments. Due to the fact that German patents are not honored in the United States, the plant management was extremely cautious about allowing Huntsinger to see certain of their new products and, in fact, did not permit him to enter several departments. He did, however, observe the manufacture of a revolutionary new derrick, fabricated from special shapes of high alloy steel. This derrick was described as comparable to our standard 136 ft derrick, but 30 per cent stronger and 13,000 lb less in weight. The interesting feature was that the increments of the derrick telescope such that the complete unit will fit into two small packing boxes for shipment. It was possibly this derrick and other developments in this plant which prompted Huntsinger to summarize the German oil industry as being ten years behind us with 90 per cent of their equipment and ten years ahead with the remaining 10 per cent.

While near Hanover, Huntsinger visited the Elwerat oil mine at Mudem. At this installation, oil of 12-14° gravity is being produced from a mine 900 ft deep. The operation is conducted on several levels by drilling holes back into the productive strata and allowing

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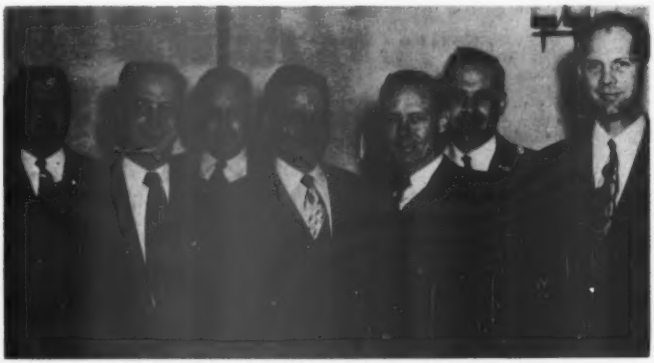

1951 GULF COAST SECTION OFFICERS, L to R, are E. L. Petree, past-chairman and director; E. F. Stratton, secretary-treasurer; E. B. Miller, director; A. W. Wadill, chairman; George Gray, vice-chairman; E. A. Rassinier, director; and Tom Borland, director. Not shown are George Fancher, vice-chairman for the University of Texas; A. B. Stevens, vice-chairman for Texas A&M College; and Herman Otto, director.

Industry and the Petroleum Engineering Schools

By Sam J. Poythress, Jr.
Mississippi Sub-Section

"It seems that things engineers do most are talk and write, and in response to one criticism of industry we have added a course in speech to our curriculum and added an advanced course in grammar," said B. C. Craft, professor of petroleum engineering at Louisiana State University, addressing a meeting of the Mississippi Sub Section at Natchez, Miss., last month.

Craft's subject was "The Coordination of Petroleum Engineering Schools with the Petroleum Industry" and principally stressed what industry can do for petroleum engineering schools.

"One of the first benefits to be received from industry is scholarships and fellowships. LSU has three fellowships and scholarships given by different oil companies; and, in addition, the Delta Section has set aside $1,000 which may be used to assist any worthy student who needs to purchase additional equipment to complete his thesis.

"It is also necessary for industry to assist in keeping courses up to date. Recently, new courses in mud testing and gas lift and pumping have been added, and a series of lectures on electric logging is given.

"Each year, the best student papers are chosen in a contest among selected seniors, and those papers are awarded prizes given by industry. In previous years, the best papers were presented before the Delta Section; but, if the Mississippi Sub-Section wishes, these papers may be given before them.

"Industry has furnished summer employment for members of the faculty, as well as students; and LSU will welcome any more assistance along that line that it can get.

"Industry must report on the graduates that a school turns out and make suggestions for improving them. There seems no sure way of developing personality now, and that is a most important characteristic.

"Industry has been generous in the donation of equipment, but much more equipment is needed. In many instances, transparent plastic models are more helpful than full scale parts for explaining the actual functioning and, in addition, is easier to carry from class to class.

"It is difficult to get enough guest speakers at a school, as the same speaker can't be used each year because soon most of the students will have heard him. If any of the companies know of any speakers available, the Petroleum Engineering Department would appreciate the companies' contacting us.

"Finally, the thing that has made us the largest department in the College of Engineering has been the successful placement of graduates. In this we are deeply indebted to industry and hope they will continue to need our men."

Two other guests spoke to the 48 assembled members. Joe B. Alford, Executive Secretary, Petroleum Branch, AIME, and E. H. Robie, Secretary, AIME, told of the past year's work and that which is planned in the year to come.

Officers for the year 1951 were elected and include J. K. Wright, Mississippi State Oil and Gas Board, chairman; T. Hardy Jackson, Jr., California Co., first vice-chairman; John A. Rodgers, Gulf Oil Corp., second vice-chairman; Eugene J. Burnet, Jr., Mississippi State Oil and Gas Board, secretary-treasurer.

J. O. Crowe, Gulf Oil Corp., and Pete Moore, Sohio Oil Co., were elected to the board of directors for the years 1951 and 1952. ★ ★ ★

Legal Aspects of Water Flooding

By Milan G. Arthur
Pacific Technology Group

The final lecture of a series on secondary recovery was presented last month to the Pacific Coast District, Petroleum Technology Group, by Mortimer A. Kline, an attorney with extensive experience in the petroleum industry. Kline spoke on the legal aspects of water flooding, and stimulated an interesting discussion following presentation of his talk.

Phases of the subject covered included general definitions, water flooding in California, availability of water in California, liability of water flood operators, the legal features of cooperative operations, conservation statutes, the model conservation act proposed by the Legal Committee of the Interstate Oil Compact Commission, and the position of cooperative operations with respect to anti-trust laws.

It was pointed out by Kline that large quantities of water are normally required for extensive water flood operations, and that there is a shortage of water in California. Regulations specify that water shall be directed to the most useful purposes. At the present time, these uses in order of accepted preference are human consumption and irrigation. The problems of prior appropriation of water supplies are most complex.

The liability of a water flood operator depends to a large extent on whether the operation is conducted as an independent act of the operator, or whether it is performed under the police power of the state through conservation statutes. Existing regulations in California were not prepared with consideration of the operation of water flood projects, and legislation is sorely needed to clarify this situation. The liabilities of the operator to lessors, and to third parties, were considered both in Kline's talk and in the discussion which followed.

Kline discussed at considerable length the number and type of state conservation statutes in the United States. Water flooding operations do not appear to violate anti-trust laws. ★

The Elk Hills Operation

By M. C. Eastman
San Joaquin Valley Section

Lieutenant Commander F. M. Tully, USN, described current and past operations of the Elk Hills reservoir last month before a meeting of the San Joaquin Section of the Pacific Petroleum Chapter. A condensed version of the description follows.

It is a conservative estimate that Elk Hills has a reserve of 650 million bbl of oil, which is the largest reserve of recoverable oil for any oil field in California, Wilmington having the next largest with a reserve of about 400 million. The Shallow Oil Zone at Elk Hills has a reserve of about 350 million bbl, having already produced 202 million. The Stevens Zone has a reserve roughly estimated at 300 million bbl, having produced thus far only 2 million bbl. The Dry Gas Zone reserve estimate is roughly 100 billion cu ft.

The MER of the Shallow Zone is probably in the neighborhood of 60,000 B/D. It is estimated that a sustained rate of 50,000 B/D could be maintained for five years with some further development to offset decline. The Stevens Zone is currently carried as having an MER of 22,000 B/D and a maximum of 62,000 B/D, the definition of the MER restricting many good producers to a zero MER. The Dry Gas Zone has a productive capacity of about 8 Mmcf/D from the six wells presently completed in that zone.

There are 564 producible wells in the Shallow Zone, 108 in the Stevens, and 6 in the Dry Gas Zone. In the Shallow Zone there are 175 to 250 more locations to be drilled. In the Stevens Zone there are 99 more wells to be drilled to complete 80-acre zonal spacing, 281 more wells for 40-acre spacing, and 675 more wells for 20-acre spacing.

Elk Hills comprises approximately 46,000 acres, 81 per cent Navy-owned and the remainder fee-owned by Standard of California. The crest of Elk Hills runs east to west bearing slightly to the northwest. The topography roughly reflects the subsurface structure which assumes more relief and definition with depth. The eastern half of the field is the most prolific both in the Shallow and Stevens zones. The bulk of the 204 million bbl produced thus far has come from the Tupman Area.

Unitization of Elk Hills was begun in 1942 and the present Unit Plan Contract between Standard and Navy was signed in June, 1944. The Amendatory and Supplementary Agreement signed in January, 1949, changed the Unit Plan Contract only to minor extents. As a compensation to Standard for relinquishing a certain degree of control over its lands, Standard received during the Primary Period of the contract 100 per cent of the Shallow Zone production up to a limit of 15,000 B/D and thus received 28,000,000 bbl of oil during the Primary Period which ended August 2 of last year. Navy pays 100 per cent of the cost of development of the field, including wells, gathering lines and gasoline plants facilities, such cost to be shared ultimately by Standard and Navy according to their respective participating interests in each zone. Since the beginning of the contract, Congress has appropriated to the Navy for the development, exploration, and operation of Elk Hills 42 million dollars of which the more recent appropriations were approximately: 9 million for Fiscal '49; 9 million for Fiscal '50; and 4 million for Fiscal '51. Congress has signified in the past that funds would be forthcoming for the full development of Elk Hills.

The surface structure of Elk Hills is marked by one large anticline about 16 miles in length and having three highs. There is a maximum oil closure of about 1,500 ft. The highs are at subsea depths of 700 ft, 800 ft, and 1,000 ft. The eastern nose of the structure is badly faulted. The western half of the Shallow Zone, on the other hand, is relatively free of faulting. The three faults on the south flank are high angle reverse faults. The rest are normal faults having dips from 45° to 90° and displacements from a few feet to 300 ft. The normal faults are found to be barriers in some places and not in others. All the faults die out with depth, with the exception of one which is known to persist from the Shallow to the Stevens Zones. It is the reverse fault in the southwest part of the field. It is visible on the surface and has a throw of about 300 ft in the Shallow Zone and 1,500 ft in the Stevens Zone.

The structure at the Shallow Zone horizon is found to be modified with depth. The wrinkle between the highs of the Shallow Zone structure becomes a deep saddle at the Stevens Zone horizon. The slopes of the flanks become steeper with depth. The Stevens Zone structure is two folds in echelon. The eastern fold which is the larger of the two has a curved axis and is observed to be fairly symmetrical. The western

1951 SOUTH PLAINS SUB-SECTION OFFICERS, L to R, are R. W. Coburn, Atlantic Refining Co., chairman; K. D. Snedeker, Kobe Incorporated, secretary-treasurer; J. B. Rosen, Stanolind Oil and Gas Co., first vice-chairman; and John Gould, Honolulu Oil Corp., second vice-chairman.

fold has a relatively straight axis but is asymmetrical because of the steeper slopes on the north flank. The crests of both structures are almost at an identical sub-sea depth of 3,620 ft, whereas the water table in the western structure is at 5,150 ft contrasting in the eastern structure to 6,000 ft in the shale and 6,600 ft in the sand. Thus there is a maximum oil closure of about 1,500 ft in the western structure and from 2,400 to 3,000 ft in the eastern structure.

The stratigraphic column thus far penetrated at Elk Hills extends from the Pleistocene to the Lower Miocene and includes the following formations: the Tulare of Pleistocene age, underlain by the San Joaquin and Etchegoin Formations of the Pliocene series, then the Reef Ridge and McLure Shales of the Upper Miocene, the Gould Shale of the Middle Miocene, and in the Lower Miocene the Media Shale, Carneros Sandstone, Santos Shale and Vaqueros Sandstone.

The Dry Gas Zone, which is found in the Central part of the field at the higher structural positions, produces from the II, III, and IV Mya sands which occur in the middle and lower San Joaquin Clay Formation at an average depth of about 2,300 ft.

The Shallow Oil Zone lies in the base of the San Joaquin Clays and in the top of the Etchegoin Formation at an average depth of about 3,000 ft.

The sands are thickest in the east end of the field and thin to the west, there being only thin sand lenses in the western half of the field. In general, the younger sands are present in the east and the older sands occur to the west. The limiting lines of productivity are defined in the western half of the field by the pinchout of the lenses. In the eastern half there is high pressure edgewater on the north and east flanks. This edgewater has been encroaching through the years as the field has been produced. On the south flank there is low pressure edgewater, so that a reverse pressure gradient exists with the possibility that oil may gravitate downstructure into gray sands.

The Shallow Zone sands are ill-sorted, argillaceous, friable, and have an average permeability of about 1,500 md. Porosity is about 35 per cent and connate water about 30 per cent. Shallow Zone edgewater has a salinity of approximately 2,000 grains per gal which makes it distinguishable in water entries from Stevens Zone water which averages about 1,000 grains per gal.

The Stevens Zone lies in the Upper Miocene McLure Shale below the Reef Ridge Shale at an average depth of about 6,500 ft. The main body of oil sand is the *B* Zone sand in the eastern part of the field. It is about 500 ft thick in the east end and thins to the west, being replaced by fractured shale. This sand is equivalent to the Lower Western sand of Coles Levee on the east. The 24Z and 26R sands in the N Zone are fairly thick but are not of too great areal extent as far as we know. The sand in the A Zone in the east end of the field is a continuation of the Upper Western sand of Coles Levee but is fairly tight and thus far almost nonproductive. Other than these sands, the Stevens Zone produces from fractured shale. It might be mentioned also that above the Stevens Zone the Olig sand in the top of the Miocene has been found to be present up to 60 ft in thickness in Section 30R and thus far appears to be mostly gas bearing. There is some gas also in the N Zone at the crest of both Stevens Zone structures.

The Stevens Zone sands are gray, and vary from tight and hard to porous and friable. They have variable permeability averaging about 150 md. Porosity is about 25 per cent and connate water about 40 per cent.

Production from the Shallow Zone was about 15,000 B/D in 1944. Wartime development increased it to 65,000 B/D by drilling 317 Shallow Zone wells. Only four of these wells were non-productive. In July, 1945, a Shallow Zone exploratory program was begun, which required the drilling of 40 wells to determine the productive limits in the southeast and the west half of the field. This proved up locations for 175 to 250 wells. Navy has under consideration at the present time to begin drilling these wells sometime later this year. It is estimated that these wells would increase the productive capacity of the field by about 18,000 B/D. Drilling time would average about 14 days per well and the cost of drilling and equipping would be about $40,000 per well. The casing program would be a surface string of 200 ft of 11¾ in., a water string of about 3,000 ft of 7 in., and completed with a 5½ in. liner and 2½ in. tubing. The vast majority of the Shallow Zone wells are pumpers with the exception of a few wells in the gas injection areas and some completed in the High Pressure Wilhelm sands. Gun perforating in the Shallow sands is to be avoided because of the resulting sand trouble. It is contemplated using oil base mud. Completion in only one or two of the several Shallow Zone sands present in a well is advisable for better control of production and reservoir conditions. Wells drilled in the 1920s were completed in several sands, and differential pressures between sands caused water migration within the well bore from a sand that had become wet to one that still contained clean oil.

The development of the Stevens Zone commenced in December, 1948. Prior

1951 DELTA SECTION OFFICERS, L to R, are (seated) Raymond B. Kelly, Jr., vice-chairman; H. M. Krause, Jr., chairman; and J. E. R. Sheeler, vice-chairman. Standing, are J. H. Homer, secretary; J. H. Rambin, director; A. L. Vitter, treasurer; and E. N. Van Duzee, director. Also elected were Murray Hawkins, director; and H. C. Loehr, Jr., Journal secretary. Fred Simmons, Jr., past chairman, automatically became a director.

to that, 38 exploratory wells had been drilled to the Stevens Zone. In the two years of the Development Program 88 wells have been drilled, averaging 6,500 ft in depth and about 35 days drilling time. The average cost per well is $125,000. Seven strings of tools were employed for the first 16 months and five during the last eight months. Drilling is by contract and usually on a modified day rate basis.

Wells are completed in either the A-N, B, or D Zones. Well density in each zone was at first limited to 160-acre spacing, whereupon interference production tests indicated that spacing could be carried to at least 80 acres in each zone. The 80-acre patterns, which we are presently drilling and which requires the drilling of 99 more wells, will be completed about the fall of 1952. The optimum spacing in the shale is somewhat dubious because of the lack of production experience in fractured shale reservoirs and the need for a measuring stick since the usual permeability, porosity, and fluid content determinations cannot be made in fractured shale. The interference tests conducted involved the producing of one or more wells in a given zone and area and observing bottom-hole pressures in these and neighboring wells over a period of time. No pressure drawdown was observed between the wells tested, the spacing varying from 40 to 80 acres.

The casing program for Stevens wells which has been found most desirable is a surface string of 200 ft of 16 in., a protective string of about 3,000 ft of 10¾ in. cemented through the Shallow Zone, a water string of about 6,000 ft of 7 in. cemented just above the zone to be produced, and completed with a 5½ in. liner and 2½ in. tubing. Liner completions are not used in wells that are to be completed down-structure near the water table nor up-structure where a gas cap may later form; instead the 7 in. is set through the producing zone and gun perforated, so that, if later production should prove wet or gassy, the interval may be squeezed off and the well completed in another zone. Water base drilling fluid is used to the top of the Stevens Zone which is then drilled with oil base mud. The change is made in open hole from water base to oil base mud without difficulty. Keeping water base mud off the producing formation gives better PI's, it is concluded from the results thus far. It is believed better cement jobs are had by mixing in the slurry a small percentage of a geling agent and also one to lighten the weight of the slurry; these agents help to prevent the cement from penetrating into the fractured formation and usually give a better cement job.

Almost all the Stevens wells are flowing wells, the static bottom-hole pressures being of the order of 3,000 psi. The MER for the average well is 210 B/D. The definition of the MER which is used, however, is conservative; it requires that the producing pressure be equal to or greater than the reservoir saturation pressure, in order to make maximum use of the gas energy. As a result, many wells which are good producers are listed as having a zero MER, since their static pressure is already less than their saturation pressure. Stevens Zone gas-oil ratios, under present reservoir conditions, generally stay within a range of 600 to 800 at the various production rates. The earlier development wells were production tested from three to six months to obtain pressure-rate, gas-oil ratio, PI, and other production characteristics at different trap pressures. Currently, Stevens wells are tested for 30 days before being shut in. Wells are produced, if capable, to a 400 psi high pressure trap and a 125 psi low pressure trap. Average gasoline content is about 1.6 gal per thousand.

The Hydrafrac process has been used in eight Stevens Zone wells thus far at Elk Hills and the results have been quite satisfactory. Seven of the wells were fractured shale completions and one was sand. Average cost of the Hydrafrac job per well was $6,500 which included rig time and involved from one to five stages of the fracturing operation per well. Substantial increases in production have been obtained in seven out of the eight cases, and in the eighth case, which was a shale well, failure may be attributable to the packer not holding during the process. The results in the one sand well Hydrafraced were not as good as the successful results obtained in the shale wells. Well 384-34S upon completion in the B Zone sand would not flow; after Hydrafracing in three stages, the well will flow at a 40 B/D rate.

A deep test well X55-30R is being drilled in the southwest part of the field to explore the Lower Miocene and possibly the Oligocene and upper Eocene. The well is currently at 8,200 ft which is about 600 ft short of the first objective, the Carneros sand. The well may be carried to 14,000 ft to the Point of Rocks if production is not obtained prior to that time. Possibility of production exists in the Carneros, Aqua, Phacoides, Oceanic, and Point of Rocks sands. In general, these sands are found in the western San Joaquin Valley; they pinch out and become impermeable to the east.

A previous deep test well, 326-28R, about two miles east was drilled to the Carneros where a small oil rise was obtained from fractured shale between two sand members which were tight. The Carneros is permeable in the Cymeric and McKittrick Front Areas to the west of Elk Hills and hence it is hoped it is permeable in test well X55-30R, which also has the advantage of being closer to the structural crest at that horizon. Hopeful prospects also exist for the Phacoides, Oceanic, and Point of Rocks sands, not yet penetrated in Elk Hills, but which are productive to the west in the McKittrick Group.

The Readiness Program was originated at the close of the last war for the purpose of maintaining the field in readiness to produce for another such emergency. Thus far it has involved only the Shallow Zone.

There is a Wet Well Program under which currently 58 wet wells are produced more or less continuously in order to protect clean sands from damage by water invasion, which is particularly likely in the more depleted areas.

Under the Rotating Test Program the clean wells are produced for a number of days once each year or once every two years, depending on their past history, in order to locate wells which may have become wet and to check the mechanical condition of the wells.

One of the main constructive projects has been the Gas Injection Program. Since September, 1945, gas produced from the Dry Gas Zone and the Stevens Zone has been injected into the SS-2 and M sand in the newly developed portion of the Shallow Zone. Varying rates of injection have been used up to 10 MMcf/D. The average datum pressure in the area has been increased from 612 to 737 psi and the productive capacity of the wells somewhat increased. The expansion of the gas cap took place rather rapidly, the expanded limits depicted being for April, 1947, and they have changed but little since. Helium was used as a tracer of the gas expansion. The channelling of the gas is attributable to a number of factors, namely: pressure gradients varying in different directions, the faults acting as pressure barriers in many instances, and the relatively high permeability variation of the sands. The wells used for injection were 84-31S, 34-32S, 37-

Continued on Page 5, Section 2

San Antonio-Austin Sub-Section and Wyoming Chapter Organized During 1950

Expansion of the Petroleum Branch in functional organizations within local areas took two steps forward during 1950 with the formation of the San Antonio-Austin Sub Section and the Wyoming Petroleum Chapter. Both organizations resulted from the work of several loyal AIME members over a period of time, and since their establishment both have rapidly assumed recognition in the AIME.

San Antonio-Austin Sub Section

The initial movement to start a functional petroleum organization in this area began about three years ago, with a meeting of AIME members in San Antonio to discuss the possibility. AIME membership in San Antonio was apparently not large enough at that time to sustain a section, and although no immediate steps were taken, interest in a local section there continued to grow. In the spring of 1950 this interest grew to the point of action, and largely through the work of Harry H. Power of the University of Texas, a meeting was called to organize a local group. The meeting was held in San Antonio May 31, with R. C. Granberry, chairman of the Southwest Texas Local Section presiding. After thorough discussion, the 30 AIME members attending voted to establish a Sub-Section of the Southwest Texas Section. A slate of officers, which had been proposed by a nominating committe headed by Thomas S. West, were elected and business was started at the first meeting. Officers are: William H. Spice, Jr., consultant, San Antonio, chairman; Harry H. Power, University of Texas, Austin, vice-chairman; and J. B. Jones, Halliburton Oil Well Cementing Co., San Antonio, secretary-treasurer. Directors are: Harry Rosser, Continental Oil Co., San Antonio, Oscar Goode, Magnolia Petroleum Co., Luling, William E. Richards, Humble Oil and Refining Co., Pleasanton, and J. H. McQuown, consultant, Austin.

To complete the formation of this sub-section, it was necessary to transfer Travis and Bastrop counties in Texas (of which Austin is the county seat of one) from the geographical area of the Gulf Coast Section to the area of the Southwest Texas Section. A study of Petroleum Branch and AIME organization was being made at the time, and this transfer was held pending its completion. The transfer was made by the AIME Board in December, 1950, and at a meeting in San Antonio on January 12, 1951, formal organization of the group was completed, and the name San Antonio-Austin Sub-Section was officially adopted.

The sub-section will have a total membership of about 60 AIME members in the area, and it is expected that meetings will be held alternately between the two cities on a monthly basis except during the summer.

Wyoming Petroleum Chapter

Interest in a functional petroleum organization within the AIME was strong in 1947, when a regional Petroleum Branch meeting was held in Denver. A number of members in the area talked of forming a Rocky Mountain Petroleum Chapter of the Petroleum Branch, and an organization meeting was planned for the Fall of 1949. Several difficulties were encountered, however, and formation of a section was not accomplished. In the spring of 1950 several AIME members in the area continued to work for a mechanism that would bring the interest of all Petroleum Branch members there to a focus. Through the work of Tom C. Heistand, Raymond M. Larsen, George L. Goodin and several others, an organization meeting was called in Casper, Wyo., on June 2. About 30 members attended, and Petroleum Branch Secretary Joe B. Alford attended from Dallas. The possibility of combining petroleum activities with the Wyoming Local Section of AIME was discussed. The group elected to petition the Petroleum Branch for a charter as the Wyoming Petroleum Chapter. A sub committee had previously drawn up a set of By-Laws for the chapter, and these were given to Secretary Alford for submission to the Branch Executive Committee. A slate of previously nominated officers was elected. They are: R. M. Churchwell, The Ohio Oil Co., Casper, chairman; Sidney B. Richards, Stanolind Oil and Gas Co., Casper, first vice-chairman; Raymond M. Larsen, U. S. Geological Survey, Casper, second vice-chairman; and George L. Goodin, Petroleum Information Inc., Casper, secretary-treasurer.

The Petroleum Branch Executive Committee approved the By-Laws and granted a charter to the Chapter in September, 1950. Meetings are now being held monthly, and the chapter is serving a real need for about 75 Petroleum Branch members in the area. ★

East Texas Section Officers

Chairman, W. W. Leonard, Continental Supply Co., Shreveport, La.

Vice-Chairman, W. R. Mays, Kilgore College, Kilgore, Tex.

Secretary-Treasurer, W. E. LaRoche, Tide Water Assoc. Oil Co., Kilgore, Tex.

Directors, Bert Crowder, Humble, Talco, Tex.; H. L. Long, Kilgore Petroleum Co., Kilgore, Tex.; J. A. Walker, Magnolia Pet. Co., Shreveport, La.; P. J. Lehnhard, East Texas Engr. Assn., Kilgore, Tex.

Continuing directors, R. K. Thies, Schlumberger Well Surveying Co., Tyler, Tex.; P. E. DesJardins, Shell Oil Co., Kilgore, Tex.; B. F. Patterson, Jr., The Texas Co., Shreveport, La.; W. S. Morris, East Texas Salt Water Disposal Co., Kilgore, Tex.

Missouri School To Hold Symposium

Missouri School of Mines and Metallurgy, under the sponsorship of its Petroleum Engineering faculty, is presenting a symposium on Water Flooding. The program will be held on the Missouri School of Mines campus in Rolla February 23 and will include the following participants: C. H. Keplinger, moderator; H. H. Power, "History of Water Flooding in U. S.;" J. C. Calhoun, Jr., "Theoretical Aspects of Water Flooding;" R. C. Earlougher, "Technical Valuation of Properties for Water Flooding;" H. S. Barger, "Sources of Water and Water Treatment;" and W. H. Davis, "A Case History of the Rosiclare Flood, Patoka Field, Illinois."

Those interested in attending the symposium are invited to participate in the discussion. The School of Mines campus is about 110 miles southwest of St. Louis and is on Highway 66 and the Frisco Railroad. If hotel reservations are desired, they will be arranged on request to the Mining Department.

★ ★ ★

Petroleum Branch Officership Eligibility List

ARTICLE VIII of the By-Laws adopted March 20, 1947, provides that:

". . . To be eligible for election to the Executive Committee a member shall have had wide experience in the affairs of the Branch . . . ."

". . . To be eligible for Chairman a member shall have three years of active service in the Branch, at least one of which shall have been as Chairman of a standing or special committee or as a member of the Executive Committee . . . ."

". . . To be eligible for Vice-Chairman a member shall have had two years of active service in the Branch, at least one of which shall have been as chairman of a standing or special committee, or as a member of the Executive Committee, or a Chairman of a Local Section . . . ."

The list below is of members who meet the specific provisions of eligibility for election to Chairman or Vice-Chairman. No attempt has been made to distinguish those who meet the non-specific portion of the eligibility requirements, i.e., "wide experience" and "three years of active service." Data after each name represents the year and type of service, according to the code below.

The Pacific Petroleum and Illinois Basin Chapters have been considered Local Sections, within the intent of the By-Laws. The list may be incomplete with respect to the earliest years of the Branch (1922-1927), as full records on that period are not available. Please call any errors or omissions to the attention of the editor.

POSITION CODE

AC	Associate Branch Chairman
BT	Branch Treasurer
Ch	Branch Chairman
CLS	Chairman, Local Section
EC	Member, Executive Committee
Ec	Chairman, Education Committee
Eco	Chairman, Economics Committee
EE	Chairman, Engineering Education Committee
ER	Chairman, Engineering Research Committee
Ge	Chairman, Geophysics Committee
Lc	Chairman, Lucas Fund Committee
Me	Chairman, Membership Committee
Nom	Chairman, Nominating Committee
PE	Chairman, Production Engineering Committee
PG	Chairman, Production Geology Committee
PP	Chairman, Papers and Programs Committee
PR	Chairman, Production Review Committee
Pro	Chairman, Progress Committee
Prod	Chairman, Production Committee
PT	Chairman, Production Technology Committee
Pub	Chairman, Publications Committee
RE	Refinery Engineering Committee
RVC	Branch Regional Vice-Chairman
SC	Chairman, Special Committee
ST	Branch Secretary-Treasurer
St	Chairman, Stabilizing Committee
TE	Transportation Engineering Chairman
VC	Branch Vice-Chairman

A - C

Akins, D. W., Jr. — CLS 47
Albertson, M. — PE 35 AC 36 Ch 37 EC 38
Alcorn, I. W. — Me 45 CLS 44 Ch 48 EC 48 49 Nom 49
Ambrose, A. W. — CLS 27 EC 30-35 Ch 28
Andrews, Paul — CLS 49 EC 49 VC 50
Armstrong, E. B. — CLS 47
Atkinson, Burton — CLS 48 Me 50
Atkinson, Thomas — CLS 47
Aucoin, Riley — CLS 45
Beal, Carlton — EC 46 ST 46 VC 48 EC 48 SC 47-48
Beams, Robert J. — CLS 48
Beardmore, H. F. — CLS 41 RVC 44 Ch 46 EC 45-46-47
Beecher, C. E. — AC 30 Ch 31 EC 32-37
Bell, John S. — PE 46 CLS 44
Bennett, E. O. — EC 35
Berwald, Wm. B. — CLS 45 EC 47
Bethancourt, Raoul — CLS 49
Blau, L. W. — Ge 43 44
Bradley, R. J. — Ec 48 49
Brown, W. F. — CLS 50
Brownscombe, E. R. — Pub 48
Buckley, S. E. — CLS 42 PP 42 EC 44-45-47-48-49 AC 44
Bunbee, J. M. — Me 43 CLS 43
Calhoun, J. C., Jr. — Ec 49
Cama, R. W. — RE 32
Carter, D. V. — PR 50
Churchwell, R. M. — CLC 50
Coberly, C. J. — AC 40 EC 41-42
Cooley, H. M. — CLS 50
Cortes, G. B. — EC 37-38-39 Ch 38
Covell, K. A. — CLS 38 PE 44
Craft, B. C. — Ec 45 ST 38-39-40 EC 44 PP 44 EC 48-49-50

D - F

Dahlgren, E. G. — PR 47-48-49
Decker, Harold — CLS 47 EC 49-50-51
Dooley, David L. — CLS 47
Duce, J. Terry — Prod 35-36-37-38-39-40-41
Dunlap, E. N. — CLS 49
Earlougher, R. C. — Pub 47 CLS 46 EC 50-51-52
Elkins, Lincoln — CLS 49
Elkins, Lloyd — CLS 45 VC 47 EC 47-49-50 Ch 49 Nom 50
Estabrook, E. L. — EC 32
Fisher, Eugene A. — CLS 46
Fisher, Gordon H. — CLS 47 Pub 49
FitzGerald, Norman D. — Ec 42-43-44
Fitzgerald, P. E. — CLS 40 ER 42 Me 44 Pub 46 VC 48 EC 48
Fohs, F. Julius — Ch 25-26
Fowler, Harry C. — EC 36 ER 32
Frick, Tom C. — CLS 47 CLS 49
French, Richard W., Jr. — PT 48 VC 50

G - K

Garrison, A. D. — ER 41
Gaylord, E. G. — EC 35 Nom 39
Geis, W. H. — AC 38 EC 39-40-41 Ch 39
Gill, John D. — EC 45-46
Gilmore, R. B. — BT 50
Gouldy, Roland — CLS 50
Granberry, R. C., Jr. — CLS 50
Graybeal, J. W. — CLS 45
Greenidge, S. M. — EC 39
Griswold, E. H. — PE 31-32
Haider, M. L. — PE 38 Pub 43-44 EC 43-45-46 Ch 45 Nom 46
Halbouty, M. T. — CLS 39 Me 40
Hamilton, R. G. — CLS 43
Hamman, Cecil A. — CLS 49
Hammond, John P. — CLS 49
Harlan, Don L. — CLS 49
Haynes, W. P. — Prod 43-44
Hayward, J. T. — ER 36
Herald, Frank A. — Prod 33-34
Heroy, W. B. — EC 39-40-41-43
Hess, Robert M. — CLS 45
Higgs, Morton T. — CLS 45
Hill, H. H. — EC 30
Hocott, Claude R. — PP 45 AC 46 EC 46
Holmes, Joseph A. — CLS 47
Huntington, R. L. — ER 37-38
Jackson, Warren J. — CLS 48
Jones, N. N. — CLS 41
Katz, D. L. — ER 39-40 PP 43 Ed 45-47
Kaveler, H. H. — ER 45 PP 46 EC 46
Kelly, R. B. — EC 37-42 AC 41
Keplinger, C. H. — CLS 37 PE 42 RVC 46 EC 46
Knappen, Russell S. — EC 32-34
Knowlton, D. R. — EC 38 EC 41
Kraus, Edgar E. — PG 46

L - P

Langford, C. M., Jr. — CLS 40
Leeton, H. B. — CLS 50
Lehnhard, Phil J. — CLS 50
Lilley, E. R. — ST 30 Pub 45
Little, W. N. — CLS 50
Loomis, A. G. — ER 44
Love, R. W. — CLS 50
Lovejoy, John M. — Ch 27 LC 32-33-34-35
Lyle, Henry — CLS 48
Manion, Peter P., Jr. — Me 47 CLS 48
Mapes, Clarel B. — EC 33-34
Marsh, H. N. — EC 32-33-36-37-38 Ch 36 Nom 40
Marshall, Dan L. — CLS 47
McCutchin, John A. — CLS 42
McMillan, John — CLS 47 EC 50-51-52
Mercier, V. J. — CLS 49
Millikan, C. V. — Ch 30 EC 33-36-40 Nom 38
Moore, T. V. — ER 35 PE 37 AC 39 Ch 40 EC 41
Morris, W. S. — CLS 40 PP 40-41 EC 43-44-45 AC 42 Ch 44 Nom 45
Moulton, Gail F. — Prod 45-45 VC 49
Murrell, John H. — CLS 46 VC 47 EC 47-48-49-50
Muskat, Morris — PT 50
Narramore, Chester — EC 44-45
Nowels, K. B. — ER 33
Nye, George L. — CLS 48
Ogden, L. A. — CLS 35
Parks, Ernest K. — CLS 45
Parks, Mercer H. — CLS 46
Parsons, B. E. — EC 34
Petree, Ernest L. — CLC 50
Pishny, Charles — CLS 45
Pollard, Terry A. — Me 48 ER 49
Pogue, J. E. — Ec 27 Ec 32
Porter, L. E. — PE 43
Porter, W. W. II — CLS 47 EC 47-48
Posgate, James — CLS 48
Power, H. H. — PE 34 EC 35-36-40 Ch 35 Me 37 Nom 41 Ec 43-44
Powers, W. D. — CLC 50
Putnam, Murray — CLC 50
Pyle, H. C. — Ch 47 EC 47-48 Nom 48

R - Z

Reistle, C. E., Jr. — EC 42 AC 43
Rhea, A. A. — CLS 42
Schultz, Paul — Eco 50
Sheldon, Dean H. — CLS 48 EC 49-50-51
Shepherd, Jack M. — CLS 49
Sherborne, John E. — ER 46 EC 47-48-49 SC 46-47 VC 49 PT 49 Ch 50
Simmons, Fred E., Jr. — CLS 50
Sinsheimer, Warren A. — EC 30-34
Smith, Veleair C. — AC 43
Spoor, H. C., Jr. — SC 49
Stephenson, Eugene A. — PE 32 ST 33-37 inc., EC 34-39-40-41-42-43 PP 38 CLS 41
Stolz, Harry P. — AC 41 Ch 42 EC 43 Pro 45
Struth, H. J. — EC 32-47
Suman, John R. — EC 32-33-34
Swensrud, Sidney A. — Ec 35-36-37-38
Teague, J. U. — CLS 41
Terry, L. F. — EC 39-40-41
Thornton, Owen — CLS 49 VC 50 Pub 50
Trostel, E. G. — ER 43 PE 45 CLS 45
Turnbull, Paul — CLS 47
Umpleby, J. B. — PE 27 Ch 29 EC 32-47 SC 46
Uren, Lester C. — Ed 45
Vance, Harold — PP 39 EC 41-42 ST 43-44
Vietti, Wm. V. — CLS 37 EC 47-48
van Wingen, N. — PT 47 CLS 50
Walker, A. W. — CLS 39 PE 41
Waddill, Alfred W. — ME 46
Warner, C. A. — CLS 38 Me 39-41 AC 42 Ch 43 EC 44 Pro 46
Wasson, H. J. — EC 35 Prod 32 EC 35
Waszkowski, Henry — CLS 50
Watson, C. P. — AC 43 Prod 30
Weaver, P. — EC 39 Me 42 Ge 45-46
Wilcox, Stanley W. — CLS 44
Wilde, H. D., Jr. — PE 33 EC 33-34-35 Ch 34
Wrather, W. E. — EC 33-34 Ch 33
Young, C. M. — EE 32-33
Zavoico, Basil — Prod 42 AC 43 RVC 43

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SPECIAL CONSIDERATIONS IN PREDICTING RESERVOIR PERFORMANCE OF HIGHLY VOLATILE TYPE OIL RESERVOIRS

ALTON B. COOK, MEMBER AIME, **G. B. SPENCER** AND **F. P. BOBROWSKI**, BUREAU OF MINES, UNITED STATES DEPARTMENT OF INTERIOR, BARTLESVILLE, OKLA.

INTRODUCTION

In estimating production gas/oil ratios and oil recoveries from reservoirs containing highly volatile oils it is highly important to include condensate that may be recovered from the gas produced from the reservoir. The volume of the hydrocarbon liquid condensed from the production of the solution gas that has been liberated in some reservoirs may equal or even exceed the volume of recoverable stock-tank oil as estimated by present methods. The usual procedure[1,2,3] in estimating future reservoir performance includes use of relative permeability data of the reservoir rock to gas and oil and includes material-balance calculations utilizing data on the volume of the reservoir fluids, oil and gas production and reservoir pressure decline, and data on the physical properties of the initial reservoir fluids. The inaccuracy in the procedure results from the false assumption that all of the free or liberated gas that enters the well bore of reservoirs containing highly volatile oils remains in the gaseous phase as it is produced.

This paper presents a method for estimating future reservoir performance and oil recoveries based on special laboratory analyses of reservoir-oil samples and recognition of the additional volume of hydrocarbon liquid that will be recovered at various stages of depletion from a solution-gas-drive reservoir. The method also includes calculations of the volume and composition of the hydrocarbon liquids that can be recovered by processing the produced gas in a natural-gasoline plant. The development of the method resulted from a study of laboratory analyses of reservoir samples and of field data obtained from two reservoirs containing oil of the highly volatile type.

Relatively high pressures and temperatures prevail in oil reservoirs discovered at the greater depths of present-day drilling. The contained fluids may have high saturation pressures and large volumes of gas in solution. The oils and gases under these conditions may be almost identical in compositions and densities.[4,5] Also, engineers have noted that, for a number of oil reservoirs and especially the deeper reservoirs, the API gravity of the stock-tank oil increases as the production gas/oil ratios increase. They attributed this increase in API gravity of the stock-tank oil to the formation of condensate as the liberated gas in the reservoir is being produced.

SOURCE OF DATA FOR CALCULATIONS

Subsurface oil samples and well-test data were obtained from the E. Constantin-Lambert Well No. 1 in the Elk City Field, Okla., to demonstrate the need for and a method of calculating future reservoir performance when consideration is given to the recoverable hydrocarbon liquid from the production of solution gas that has been or will be liberated in a reservoir. The Lambert well is located in C. SW¼, SW¼, Sec. 18, T-10-N, R-20-W, Washita County, Okla. At the time of completion it was on the east edge of the development and was producing from conglomerate through 30 perforations in the 5½-in. casing at a depth of 9,859 to 9,864 ft. The well was completed on July 9, 1949, and subsurface oil samples were obtained July 29 and August 1, 1949. Production gas/oil ratio data were obtained during the operation in series of two separators at high and low-pressures of 314 and 44 psia, respectively, and at an average temperature of approximately 60°F. The flowing bottom-hole pressure at the time of sampling was 3,934 psia. The static bottom-hole pressure was not obtained at the time of sampling, as the well could not be shut in long enough for testing because gas produced from the well was used for fuel at an offset drilling well. However, the initial reservoir pressure was calculated to be 4,364 psia from knowledge of pressure gradients in other wells in the field and the depth of the casing perforations in the Lambert No. 1 well.

[1]References given at end of paper.

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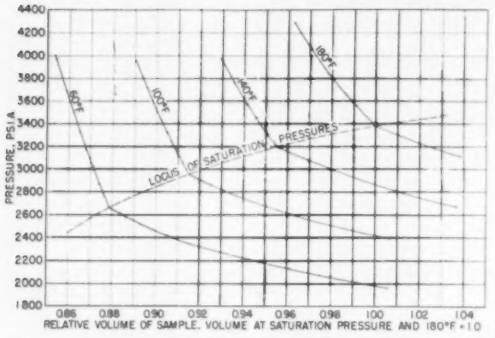

FIG. 1 — PRESSURE-VOLUME-TEMPERATURE RELATIONSHIPS OF SUBSURFACE OIL SAMPLE FROM CONSTANTIN-LAMBERT WELL NO. 1, ELK CITY FIELD, WASHITA COUNTY, OKLA.

The saturation pressure of the duplicate subsurface oil samples was found to be 3,383 psia. The solution gas/oil ratio as determined in the laboratory by the flash-gas liberation method, conducted to simulate producing conditions, was 2,172 cu ft of gas per barrel of stock-tank oil at the separator operating pressure of 314 psia. As this compares favorably with the measured production gas/oil ratio of 2,140 cu ft of gas per barrel of stock-tank oil and as the saturation pressures of the two subsurface oil samples were identical, the subsurface oil samples were considered representative of the initial reservoir oil.* Laboratory data on the samples are shown in Table I and Figs. 1, 2, 3, and 4.

Fig. 1 shows pressure-volume relationships of the reservoir oil at four temperatures — 60°, 100°, 140°, and 180°F. It is of interest to note that the degree of expansion with pressure reduction of the reservoir oil sample at 180°F (reservoir temperature) is almost as great while in the liquid phase as it is after the pressure has been reduced below saturation pressure. The expansion of the liquid phase in a reservoir containing an undersaturated highly volatile oil may account for a large part of the ultimate recovery. Fig. 2 and Table I shows data obtained by the differential gas-liberation procedure. Almost 3,400 cu ft of gas was liberated per barrel of residual oil at 60°F, which caused a reduction in the liquid volume from 3.041 to 1.0. The first gas liberated from the reservoir was almost as dense as air, indicating that the gas was rich in condensable hydrocarbons. The flash gas-liberation experiment (Table I and Fig. 3) conducted to simulate producing conditions when two separators were operated in series, shows that 2,594 cu ft of gas was liberated per barrel of stock-tank oil and that the production of 2.508 bbl of initial reservoir oil was necessary to yield 1 bbl of stock-tank oil. Pressure-viscosity data of the reservoir oil at 180°F are presented in Fig. 4. The viscosity of the Elk City Field reservoir oil was only 0.135 centipoise at the saturation pressure and reservoir temperature; the viscosity is less than that of water, which under the same conditions is 0.35 centipoise.

For the purposes of this study idealized reservoir conditions were assumed because certain necessary data on the Elk City Reservoir were not available. Reservoir conditions were as follows:

1. An initial pressure and temperature of 4,364 psia and 180°F, respectively, existing in the reservoir penetrated by the Constantin-Lambert Well No. 1 in the Elk City, Okla., Field.
2. Initial reservoir oil having the physical properties of the subsurface oil samples obtained from the lambert Well (Table I and Figs. 1, 2, 3, and 4).
3. Relative permeability (K_g/K_o) of reservoir rock as reported by Muskat and Taylor[6] (Fig. 5).
4. Viscosity of reservoir gas as determined by the procedure developed by Bicker and Katz[7] [Fig. 6 for relative viscosity of oil to gas (U_o/U_g)].
5. Solution-gas-drive reservoir.
6. For reservoirs containing volumes of oil and water as follows:

Table I — Differential and Flash Gas-Liberation Data on a Subsurface Oil Sample from Constantin-Lambert Well No. 1, Elk City Field, Washita County, Okla.

Pres., psia	Temp., °F	Relative oil volume, residual oil volume at 60°F = 1.0	Density[1] of liberated gas, gm./ml. (gas at 60°F and 14.4 psia)	Oil density, gm./ml.	Gas in solution, cu ft per bbl of residual oil at 60°F (gas at 60°F and 14.4 psia)
		Differential gas liberation			
4,365[2]	180	3.041		0.491	3,393
3,383[3]	180	3.166		.472	3,393
3,300	180	2.997	[4] 0.001178	.481	3,144
3,183	180	2.792	.001142	.493	2,826
2,918	180	2.515	.001080	.512	2,360
2,673	180	2.330	.001038	.527	2,038
2,208	180	2.074	.000997	.554	1,593
1,378	180	1.781	.000968	.591	1,034
683	180	1.586	.000974	.623	659
192	180	1.427	.001126	.652	376
14.4	180	1.076	.001998	.741	0
14.4	60	1.000		.7970	0
		Flash gas liberation (two separators)			
4,365[2]	180	[5] 2.508		[5] 0.491	2,594
3,383[3]	180	2.612		[5] .472	2,594
3,300	180	[5] 2.472		[5] .481	[5] 2,383
3,183	180	[5] 2.304		[5] .493	[5] 2,113
2,918	180	[5] 2.075		[5] .512	[5] 1,717
2,673	180	[5] 1.922		[5] .527	[5] 1,444
2,208	180	[5] 1.711		[5] .554	[5] 1,070
314.4[6]	60	1.237	[4] .000886	.719	422
44.4[6]	60	1.076	.001396	.755	114
14.4	60	1.000	.001998	.7726	0
		Flash gas liberation (one separator)			
4,365[2]	180	[5] 2.624		[5] 0.491	2,812
3,383[3]	180	2.732		[5] .472	2,812
3,300	180	[5] 2.586		[5] .481	[5] 2,597
3,183	180	[5] 2.409		[5] .493	[5] 2,323
2,918	180	[5] 2.170		[5] .512	[5] 1,921
2,673	180	[5] 2.010		[5] .527	[5] 1,643
2,208	180	[5] 1.790		[5] .554	[5] 1,263
64.4[6]	60	1.044	[4] .001015	.760	69
14.4	60	1.000	.001580	.7737	0

[1]Gas density x 834.4 = specific gravity (air = 1.0).
[2]Initial reservoir pressure.
[3]Saturation pressure.
[4]Gas densities, representative of the gas liberated between two pressures, are shown opposite the lowest pressure at which gas was liberated.
[5]Calculated by using "differential gas-liberation data."
[6]Gas-Oil separator pressure.

*These samples should not be considered average for the Elk City, Okla., Field as considerable variations are reported in gas/oil ratios and API gravities of produced oil for the initial tests on wells in the field.

(a) 1,428,600 bbl of pore space containing 1,000,000 bbl of initial reservoir oil and 428,600 bbl of interstitial water (30 per cent).

(b) 1,190,500 bbl of pore space containing 1,000,000 bbl of initial reservoir oil and 190,500 bbl of interstitial water (16 per cent).

(c) 1,000,000 bbl of pore space containing 700,000 bbl of initial reservoir oil and 300,000 bbl of interstitial water (30 per cent).

(d) 1,000,000 bbl of pore space containing 840,000 bbl of initial reservoir oil and 160,000 bbl of interstitial water (16 per cent).

Although the physical properties of the reservoir oil from the Elk City Field are unusual as compared to most reservoir oils, other reservoirs containing oils of the highly volatile type are known; an exceptionally volatile reservoir oil has been described by Sloan.[4] In an effort to show comparisons between the ultimate recovery estimated for the Elk City Reservoir and that for other fields of this type, parallel calculations were made, using the information reported by Sloan.

The initial reservoir pressure and temperature in the unidentified field was 5,252 psia and 212°F, respectively; the reservoir contained an undersaturated oil with a saturation pressure of 4,648 psia. The production separator-gas/stock-tank-oil ratio was 3,390 cu ft per bbl and the formation volume factor was 3.12 when the single-phase reservoir liquid passed through a separator operating at a pressure of 490 psia.

The parallel calculations were made, using the reservoir pressure and temperature and the properties of the reservoir oil reported by Sloan. Recoveries were estimated only for the reservoirs containing 30 per cent interstitial water.

DEVELOPMENT OF A METHOD FOR ESTIMATING RESERVOIR PERFORMANCE

Estimating Reservoir Performance

To calculate the volume of condensate that will be collected in stock tanks or the LPG (liquefied petroleum gas) products that can be extracted by a natural gasoline plant from the production of the solution gas that has been or will be liberated in a reservoir, the following information must be known

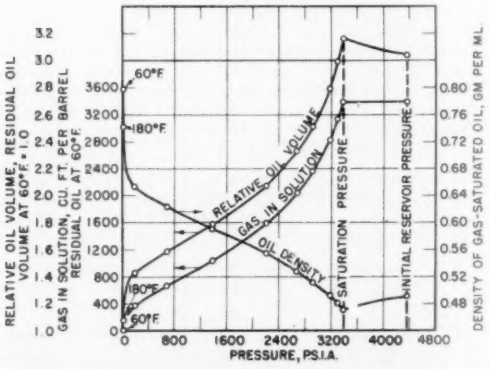

FIG. 2 — DIFFERENTIAL GAS-LIBERATION DATA AT 180°F, SUBSURFACE OIL SAMPLE, CONSTANTIN-LAMBERT WELL NO. 1, ELK CITY FIELD, WASHITA COUNTY, OKLA.

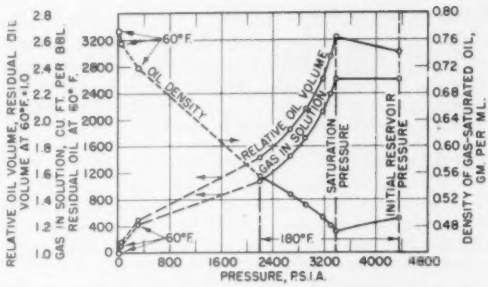
RELATIVE OIL VOLUME, RESIDUAL OIL VOLUME AT 60°F.=1.0
GAS IN SOLUTION, CU. FT. PER BBL. RESIDUAL OIL AT 60° F.
DENSITY OF GAS-SATURATED OIL, GM. PER ML.
PRESSURE, P.S.I.A.
60°F
180°F
OIL DENSITY
RELATIVE OIL VOLUME
GAS IN SOLUTION
SATURATION PRESSURE
INITIAL RESERVOIR PRESSURE

FIG. 3 — FLASH GAS-LIBERATION DATA (TWO SEPARATORS), SUBSURFACE OIL SAMPLE, CONSTANTIN-LAMBERT WELL NO. 1, ELK CITY FIELD, WASHITA COUNTY, OKLA.

for all reservoir pressures: (a) The composition of both the oil and gas flowing in the reservoir; (b) the flowing gas/oil ratios in the reservoir (the volumes of gas and oil for each selected pressure decrement); and (c) the volume of condensate for each standard-unit volume of reservoir gas. The authors have developed a technique for obtaining the desired laboratory data and a method of calculating the compositions of reservoir oil and gas for pressures below saturation pressure. Several writers[1,2,3] have contributed to a method for calculating volumes of reservoir gas and oil that will be produced with reductions in reservoir pressure when the volume of the reservoir and certain physical properties of the reservoir rock and fluids are known. Also, Katz and Hachmuth[4] have published equilibrium constants, and Katz[5] has devised a method for calculating gas/oil ratios when the composition of the reservoir fluid is known. Although the method of calculating gas/oil ratios and the equilibrium constants were developed for use in calculating recoveries from the production of liquid-phase hydrocarbons, they also can be used to predict production gas/condensate ratios when the composition of the gas entering the producing wells is known.

With the above information available a new procedure for estimating hydrocarbon-liquid recoveries was developed. It is divided into four major steps as follows:

1. The volumes of oil and liberated gas flowing in the reservoir were calculated for each of 12 assumed reservoir-pressure decrements.
2. The composition of a unit volume of the flowing oil and of the liberated gas in the reservoir were calculated for each of the pressure decrements used in step 1 above.
3. The liquid volume of the various recovered hydrocarbons was calculated from the data obtained under steps 1 and 2; all of the produced fluids were assumed to be processed by a gasoline plant that had an assumed processing efficiency.
4. The volume of recoverable condensate was calculated from equilibrium constants. (The gas liberated in the reservoir and the reservoir oil were assumed to have been produced separately through separators operating at the same pressures as are used in the field.) The volume of recoverable hydrocarbon liquid was the sum of the volume of stock-tank oil (estimated from the volume of reservoir oil entering the producing wells) and the volume of condensate (estimated recovery from the gas entering the producing wells).

The calculation procedures are outlined in more detail in the appendix.

Composition of Reservoir Gas

The gas-liberation process in a reservoir initially containing oil having a high saturation pressure with relatively large quantities of dissolved gas is neither essentially that of the "differential" or "flash" type.* This conclusion was substantiated by material-balance calculations based upon data obtained on the reservoir and subsurface samples of the Elk City Field. The results, illustrated in Fig. 7, show that from the saturation pressure of 3,383 to 2,800 psia almost all of the gas liberated in the reservoir was retained in the reservoir. From 2,800 to 2,000 psia the rate of gas liberation in the reservoir approximates the rate of gas production from the reservoir. From 2,000 psia to abandonment pressure the rate of gas production from the reservoir exceeds the rate of gas liberation in the reservoir, with the result that gas previously liberated is being produced. Thus, during the early pressure depletion of the reservoir the gas-liberation process is essentially the flash type. In the intermediate stage of pressure depletion the gas-liberation process approaches the differential type as the rate of gas liberation approximates the rate of gas production, but differs from this type because of the close association of the oil in the reservoir with large quantities of gas previously released. In the final stage of pressure depletion the rate of gas production exceeds the rate of gas liberation in the reservoir, indicating that the gas-liberation process does not simulate either the differential or the flash type.

Because of the complicated nature of the gas-liberation process and the phase changes that take place in the liberated gas as the pressure is depleted in reservoirs containing highly volatile oils, duplication of this process in the laboratory would be extremely difficult. This, however, is unnecessary as the volume of recoverable hydrocarbon liquid can be determined from data on the composition and volume of each fluid (the reservoir oil and the reservoir gas) entering the wellbores of the producing wells for each pressure decrement. The composition of the liberated gas in a reservoir apparently depends upon the reservoir pressure, within the pressure range in which retrograde condensation occurs, and not the process by which the gas is liberated, as indicated both from theoretical considerations and experimental data obtained on samples of oil and gas from the Elk City Field. Reservoir conditions are simulated in Fig. 8 to illustrate the effect of pressure reduction on the composition of liberated gas in oil reservoirs. If the system undergoes a pressure decrement a minute quantity of gas will be liberated from the oil and collected at *A* and a small quantity of liquid will be condensed from the gas and collected at *B*. If the decrease in pressure is small the compositions of the oil and gas are not affected materially, and thus the oil and gas remain in equilibrium. Also, the liberated gas is in equilibrium with the oil. Therefore, the liberated gas has essentially the same composition as the gas-cap gas, because both gases are in equilibrium with the same oil. Likewise the condensate trapped at *B* is essentially identical to the oil because both the oil and condensate are in equilibrium with the same gas. (The condensate formed in a gas cap directly overlying oil actually may not be identical to the oil, as the oil may contain solid particles in suspension.) With further reduction of pressure on the system, the first liberated gas collected at *A* will undergo the same changes owing to retrograde condensation as the gas-cap gas, and the first condensate collected at *B* will undergo the same gas-liberation conditions as the oil. Thus, it seems logical to assume that, within the pressure range in which retrograde condensation occurs, the gaseous phase of the gas-cap gas will be identical in composition to the gas being liberated.

*In the differential-gas liberation procedure the gas is removed, as it is liberated, from contact with the oil. In the flash-gas liberation procedure the gas remains in contact with the oil throughout the liberation process.

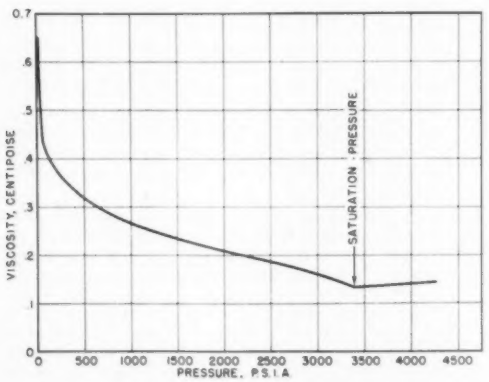

FIG. 4 — PRESSURE-VISCOSITIES AT 180°F, SUBSURFACE OIL SAMPLE, CONSTANTIN-LAMBERT WELL NO. 1, ELK CITY FIELD, WASHITA COUNTY, OKLA.

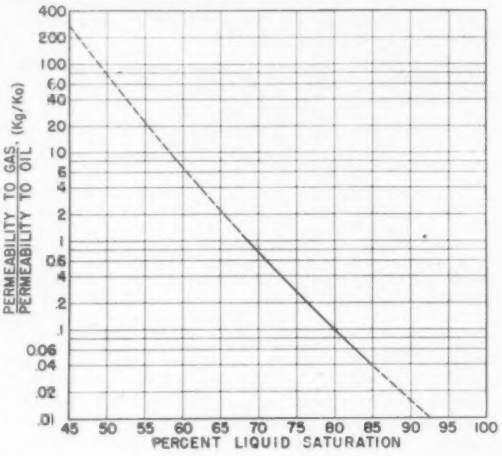

FIG. 5 — PERMEABILITY-SATURATION CURVE USED IN CALCULATIONS OF RESERVOIR PERFORMANCE.

Experimental work conducted on the Elk City Field sample to substantiate the foregoing theory consisted of determining the specific gravity of gases, at standard conditions, liberated under the following conditions in a P-V cell:

1. Gas was liberated differentially at 180°F from a sample of reservoir oil in 18 pressure steps from saturation to atmospheric pressure.
2. Three samples of reservoir oil were flashed separately at 180°F from saturation pressure to 2,500, 2,000, and 1,500 psia, respectively, and the gases were displaced from the P-V cell at constant pressure.
3. Gas was flashed in a P-V cell from a sample of reservoir

oil at 180°F from saturation pressure to 3,100 psia. The liberated gas was transferred by mercury displacement at a constant pressure from the P-V cell to another P-V cell. The gas was then liberated from the second P-V cell at 180°F in nine pressure steps.

A graph of specific-gravity data obtained by the three procedures described above is shown in Fig. 9. A study of these data shows the specific gravities of the liberated gases to be identical, within the limits of experimental error, for all pressures within the pressure range in which retrograde condensation occurs. The authors concluded that the composition of the gas in the reservoir depends only upon the reservoir pressure throughout the pressure range in which retrograde condensation occurs, as has been shown by theory and laboratory data. Accordingly, gas samples can be obtained, within the pressure range in which retrograde condensation occurs, by either the differential or flash gas-liberation procedure that will be representative of the liberated gas in the reservoir.

The composition of the reservoir gas* from the Elk City Field was obtained by fractional distillation of gas samples liberated by flashing the reservoir oil at reservoir temperature in seven pressure steps from saturation pressure to atmospheric pressure. The gas liberated in each flash step was released through the throttling valve while a constant pressure was maintained in the P-V cell. The gas released from the P-V cell passed through capillary steel tubing to low-temperature fractional gas-analysis equipment, where its composition was determined. Condensation within the capillary tubing was prevented by maintaining the absolute pressure at less than 200 mm of mercury and the temperature of the tubing at slightly above reservoir temperature. After all the gas had been liberated and analyzed, the residual oil was transferred from the P-V cell to the fractional analysis equipment, where it was analyzed. The composition of the liberated gases are shown in Fig. 10. The composition of the residual oil is given in Table II.

*The gas obtained from the flash gas liberations is not representative of the reservoir gas in the pressure range below that in which retrograde condensation occurs (below 1400 psia for the Elk City Field gas) This discrepancy is believed to be of little consequence in estimating reservoir performance because the difference between the gas obtained in the laboratory with that in the reservoir is not appreciable until the pressure decreases below 800 to 600 psia, at which time most of the recoverable reservoir fluids have been produced.

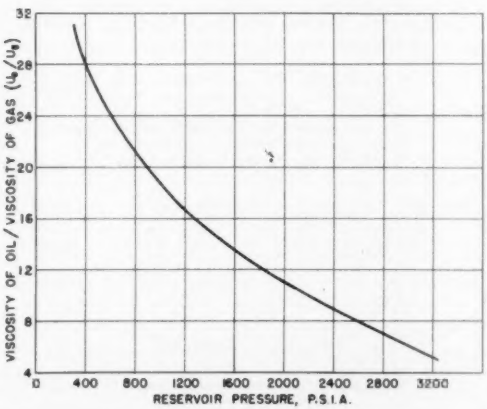

FIG. 6 — OIL AND GAS VISCOSITY RELATIONSHIPS USED IN CALCULATING RESERVOIR PERFORMANCE.

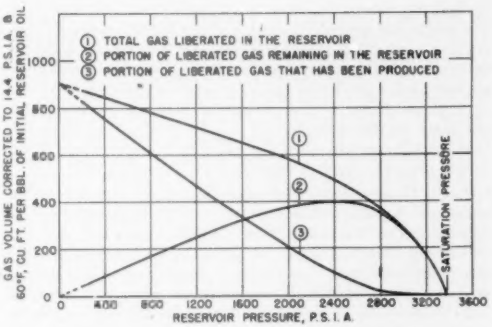

FIG. 7 — DISTRIBUTION OF GAS LIBERATED IN THE RESERVOIR PER BARREL OF INITIAL RESERVOIR OIL (ELK CITY FIELD).

CALCULATED RESERVOIR PERFORMANCE

Calculations were made for several hypothetical reservoirs for a number of declining pressure steps to abandonment pressure. The Elk City Field data and data on a field reported by Sloan[6] were used to determine (a) the production gas/oil ratio and the volume of oil produced, assuming that all of the hydrocarbons entering the producing wells in the gaseous phase passed through the gas-oil separator as gas, (b) the production gas/oil ratio and the volume of produced stock-tank hydrocarbon liquid when consideration was given to the volume of condensate resulting from the production of gas that had been liberated in the reservoirs and would be collected in the stock tanks along with the oil, and (c) the volumes of gas and hydrocarbon liquids recoverable when all produced gas was processed by a natural-gasoline plant (the gasoline plant was assumed to recover all hydrocarbons except the methane, ethane, 50 per cent of the propane, 10 per cent of the butanes, and 5 per cent of the pentanes).

The foregoing calculations were made using the Elk City Field data for four solution-gas-drive reservoirs previously described. Similar calculations limited to reservoirs described above, were made using data reported by Sloan.

Two interstitial water contents were chosen to show the extent to which these variations would affect the reservoir performance when using the Elk City Field data. An interstital water content of 30 per cent was chosen as being typical of many reservoirs. A water content of 16 per cent was obtained from core-analyses data[16] from the North Lindsay Field, Okla., a deep-seated reservoir containing a highly volatile oil.[4]

The results of the calculations to determine reservoir performance are summarized in Table III and illustrated graphically in Figs. 11, 12, 13, and 14. These data indicate that a large part of the recoverable hydrocarbon liquid from deep-seated reservoirs containing highly volatile oil, produced by the solution-gas-drive mechanism, is obtained from the production of the solution gas liberated in the reservoir. They also indicate that a greater ultimate oil recovery will be obtained from a reservoir containing a highly volatile oil if it contains nearly an average quantity of interstitial water instead of a relatively small quantity.

Data presented in Table III (columns 4 and 5) show that ultimate recovery based upon the production of the liquid-phase reservoir fluid alone can be considerably in error. In reservoirs containing oil of the Elk City type the error is 22 to 35 per cent; in reservoirs containing oil of the type de-

scribed by Sloan the error is approximately 350 per cent. The additional recovery is hydrocarbon liquid condensed during the production of solution gas that was liberated in the reservoir. The recovery can be increased even further by processing the produced gas in a gasoline plant, as is shown in columns 5 and 6. The additional recovery by processing the gas is 50,000 to 60,000 bbl of LPG products for each million bbl of reservoir oil of the Elk City Field type and about 70,000 bbl from the type described by Sloan.

Table III also shows the effect of variations in interstitial water on the calculated hydrocarbon-liquid recoveries. Calculations were made by using the Elk City Field data for interstitial water contents of 30 and 16 per cent. Values shown in lines 3, 4, 7 and 8 are based upon 1,000,000 bbl of pore space. Although the reservoir with an interstitial water content of 30 per cent contains less oil than a similar reservoir with a content of 16 per cent, the estimated ultimate stock-tank hydrocarbon-liquid recovery is greater. A graphical comparison of the recovery from two reservoirs, each containing 1,000,000 bbl of oil initially but one having 30 per cent interstitial water and the other 16 per cent, is shown in Fig. 14.

EFFECT OF OIL VOLATILITY ON RESERVOIR PERFORMANCE

Data developed in this paper on two highly volatile reservoir oils show that only a small part of the stock-tank oil initially in place will be produced by the solution-gas-drive mechanism. Some pertinent observations are set forth to show reasons for the low recovery.

The changes in oil and gas saturations that take place in a solution-gas-drive reservoir are illustrated in Fig. 15 on the basis of data on the reservoir oil from the Elk City Field. The components (70 per cent oil and 30 per cent interstitial water) of one volume of reservoir pore space initially in the

Table II — Fractional Analyses of Oil and Gas Samples from Constantin-Lambert Well No. 1, Elk City Field, Washita County, Okla.

Component	High-pressure separator (314 psia and 60°F) Gas	High-pressure separator (314 psia and 60°F) Oil	Low-pressure separator (44 psia and 60°F) Gas	Low-pressure separator (44 psia and 60°F) Oil	Initial reservoir oil[1]	Residual oil from diff. lib.
	Mole Fraction					
Carbon dioxide	0.0017	0.0003	0.0026		0.0014	
Nitrogen	.0335	.0002	.0087		.0200	
Methane	.7391	.0547	.3572	0.0005	.5372	
Ethane	.1150	.0686	.2238	.0226	.0994	
Propane	.0735	.1424	.2488	.1090	.0863	
Isobutane	.0067	.0388	.0392	.0437	.0129	0.0065
Normal butane	.0173	.1055	.0744	.1135	.0392	.0320
Isopentane	.0029	.0443	.0175	.0521	.0148	.0253
Normal pentane	.0030	.0552	.0144	.0686	.0179	.0424
Hexanes	.0020	.0851	.0119	.0985	.0200	.0501
Heptanes plus	.0053	.4049	.0015	.4915	.1509	.8437
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Specific gravity of C_7+ residue	[2]	0.810	[2]	0.811	0.809	0.815
Molecular weight of C_7+ residue	[2]	180	[2]	182	178	179

[1]Calculated from data on the volume and composition of the residual oil and the liberated gas.
[2]Insufficient residue for determination of this value.

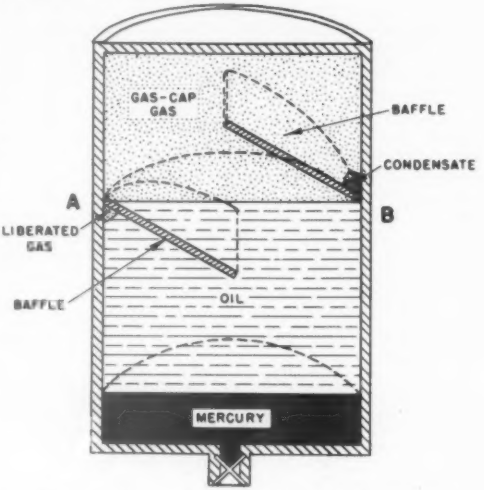

FIG. 8 — ILLUSTRATION OF OIL AND GAS IN EQUILIBRIUM.

reservoir at saturation pressure would expand with declining pressures according to curve *A*. If gas were liberated from one unit volume of the initial fluid without producing any liquid the decrease in liquid volume resulting from liberation of solution gas would be represented by curve *B* (calculated from shrinkage data obtained through a differential gas-liberation analysis). Curve *C* shows the liquid saturation as calculated by using K_g/K_o relationships and material-balance equations. Curve *D* indicates a constant interstitial water content of 30 per cent. The relative oil saturation is indicated by the horizontal distance between curves *D* and *C*. The volume of reservoir oil produced is indicated by the horizontal distance between curves *C* and *B*. As the pressure is reduced below saturation pressure and until the production gas/oil ratio exceeds the solution gas/oil ratio, the volume expansion of the reservoir oil and that of the liberated gas equals the volume of reservoir oil produced; during the pressure reduction the gas saturation is equal to this expansion plus the shrinkage of the reservoir oil. A large expansion as compared to the shrinkage is therefore an advantage.

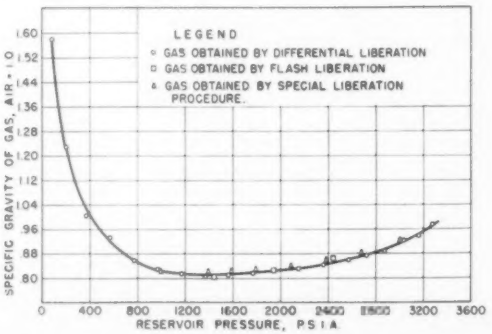

FIG. 9 — SPECIFIC GRAVITY OF LIBERATED GAS (ELK CITY FIELD, OKLA. SAMPLES).

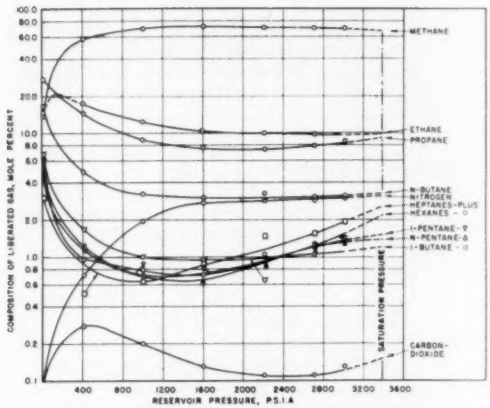

FIG. 10 — VARIATION IN COMPOSITION OF LIBERATED GAS WITH REDUCTION IN PRESSURE (ELK CITY FIELD, OKLA., SAMPLE).

type of oil. The data used to construct these curves were obtained on reservoir samples from the Elk City Field, a field reported by Sloan,[6] the West Edmond, Okla., Field,[11] and the Elk Hills, Calif., Field.[12] (The curves are lettered to correspond with those in Fig. 15). In comparing curves *B* it is apparent that the more-volatile oils undergo a greater shrinkage for a given pressure decrement than the less-volatile type. Curves *A* show that the more-volatile oils expand at a slower rate than the less-volatile oils when the pressure is first reduced below saturation pressure. Thus, for a small reduction in pressure below saturation pressure, there is little expansion of the more volatile oil to expel the reservoir oil to the producing wells whereas the gas saturation due to shrinkage of the oil increases rapidly. As a result, only a small volume of oil will be produced before the production gas/oil ratio exceeds the solution gas/oil ratio. As the pressure is reduced further on this type of oil, additional shrinkage takes place, and the gas saturation in the reservoir increases until almost all of the produced fluid is reservoir gas.

As the expansion exceeds the shrinkage for a small pressure drop below saturation pressure in the less-volatile type

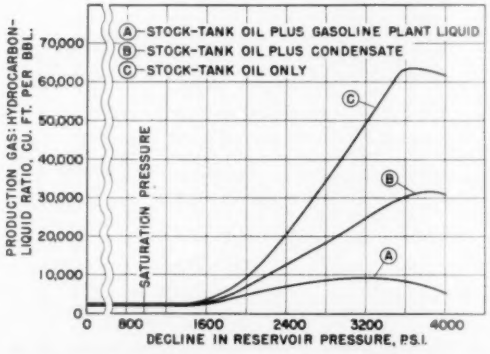
A—STOCK-TANK OIL PLUS GASOLINE PLANT LIQUID
B—STOCK-TANK OIL PLUS CONDENSATE
C—STOCK-TANK OIL ONLY
SATURATION PRESSURE
PRODUCTION GAS: HYDROCARBON-LIQUID RATIO, CU. FT. PER BBL.
DECLINE IN RESERVOIR PRESSURE, P.S.I.

FIG. 11 — GAS/HYDROCARBON-LIQUID RATIOS AS OBTAINED FROM THREE DIFFERENT METHODS OF CALCULATIONS (ELK CITY FIELD DATA BASED UPON 30 PER CENT WATER SATURATION).

of reservoir oil, these properties are the reverse of those of the more-volatile oil. For example, for a pressure drop in the Elk Hills (Calif.) Reservoir that will cause an expansion of 8 per cent, the shrinkage of the oil is only 2 per cent. A gas saturation in the reservoir of 10 per cent (8 per cent expansion and 2 per cent shrinkage) is considered to be approximately the minimum at which gas will flow.[13] Thus, as the expansion equals the production, approximately 8 per cent of the reservoir oil would be produced before the production gas/oil ratio exceeds the solution gas/oil ratio. In contrast, the curves from data reported by Sloan show that only 0.15 per cent of the oil will be produced when the gas saturation of the reservoir equals 10 per cent. The low-recovery efficiency from a highly volatile oil reservoir results from the extremely high rate of oil shrinkage and the low rate of expansion of the oil and liberated gas when pressure are decreased below saturation pressure.

SUMMARY

Methods of calculating the volume and composition of hydrocarbon liquid condensed from the produced solution gas that has been liberated in a reservoir are presented in this report. Laboratory data on reservoir-oil samples from the Elk City Field and a highly volatile reservoir oil reported by Sloan[6] were used to show that a large part of the recoverable hydrocarbon liquid from a highly volatile oil reservoir, produced by the solution-gas-drive mechanism, is obtained from the gas-phase fluid entering the producing wells. The calculations show that 18 to 26 per cent of the ultimate stock-tank liquid recovered from the hypothetical reservoirs containing oil of the Elk City Field type will be condensate and approximately 78 per cent of the stock-tank liquid recovered from a reservoir containing oil of the type reported by Sloan will be

Table III — Ultimate Recovery of Highly Volatile Oils Under Various Reservoir Conditions

	1	2	3	4	5	6
				Calculated ultimate hydrocarbon-liquid recovery, bbl[1]		
Line No.	Volume of oil in reservoir initially, bbl	Abandonment pressure, psia	Interstitial water content, pct of reservoir pore space	Stock-tank oil only	Stock-tank oil plus condensate	Stock-tank oil plus gasoline plant liquid
	Elk City Field Sample Data					
1	1,000,000	500	30	83,000	101,000	149,000
2	1,000,000	500	16	58,000	77,000	127,000
3	700,000	500	30	58,200	71,000	105,000
4	840,000	500	16	49,000	65,000	106,000
5	1,000,000	200	30	85,000	105,000	167,000
6	1,000,000	200	16	58,000	79,000	142,000
7	700,000	200	30	60,000	74,000	117,000
8	840,000	200	16	49,000	67,000	120,000
	Sample Data Reported by Sloan					
9	1,000,000	500	30	17,000	75,000	142,000
10	700,000	500	30	12,000	53,000	99,000
11	1,000,000	200	30	17,000	76,000	151,000
12	700,000	200	30	12,000	53,000	106,000

[1]These values include the production from initial reservoir pressure to saturation pressure. The expansion of 1 million bbl of initial reservoir oil to saturation pressure would yield 15,600 bbl of stock-tank oil for the Elk City Field sample data and 11,000 bbl for the sample data reported by Sloan.

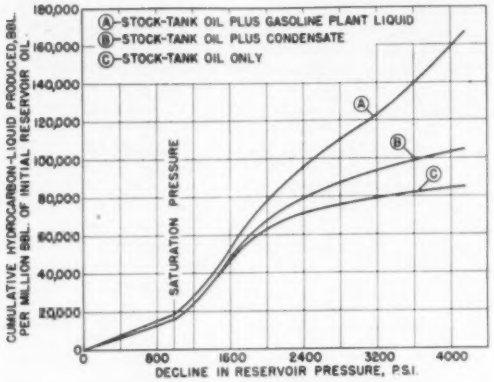

FIG. 12 — VARIATIONS IN HYDROCARBON-LIQUID RECOVERIES OBTAINED BY USING THREE DIFFERENT METHODS OF CALCULATIONS (ELK CITY FIELD DATA BASED UPON 30 PER CENT WATER SATURATION).

Fig. 16 illustrates why recovery of highly volatile oil from a reservoir will be less, even though more energy per unit volume of initial oil is available, than for the less-volatile condensate. Processing the produced gas in a gasoline plant would increase the hydrocarbon-liquid recoveries, in the form of LPG products, by approximately 50 to 100 per cent (50,000 to 70,000 bbl per 1,000,000 bbl of highly volatile oil initially in the reservoir).

Theoretical considerations and experimental results are presented to show that the gas phase in the reservoir can be duplicated in the laboratory, for the declining pressure range in which retrograde condensation occurs, by either the differential or flash gas-liberation procedure. In determining the compositions of the fluids flowing in the Elk City Field reservoir low-temperature fractional analyses of the gas obtained by the flash gas-liberation procedure were used.

APPENDIX

OUTLINE FOR CALCULATING FUTURE RESERVOIR PERFORMANCE

With the detailed information on the reservoir and reservoir fluid available, the recovery of hydrocarbon fluids for a number of reservoir-pressure decrements can be estimated by the procedure outlined in detail below. The volumes of gas and oil flowing in the reservoir are calculated by using material-balance equations.[1,2,3] The composition of the fluids — oil and gas — flowing in the reservoir are calculated from data on the compositions of the residual oil and liberated gas and gas solubility obtained in the laboratory. From knowledge of the volumes and compositions of the fluids flowing in the reservoir the total volumes of the stock-tank oil and the LPG products that can be extracted in a gasoline plant are determined. Equilibrium constants [4,5] and knowledge of the composition of the reservoir gas are used in calculating the volume of stock-tank condensate that will be recovered from the production of the solution gas that has been liberated in the reservoir.

A. Gas/Oil Ratios for the Fluids Flowing in the Reservoir.

(1) Plot "K_v/K_o versus liquid saturation," Fig. 5.

(2) Calculate viscosity of gas for reservoir temperature and several pressures. Obtain viscosity of oil for the same pressures. Calculate and plot U_o/U_g, Fig. 6.

(3) Use flash-gas liberation data (Fig. 3) in material-balance equations and calculate oil and gas production.

(4) Summarize oil and gas production.

B. Gasoline-Plant Calculations.

(1) Liquid composition (volume fraction) of reservoir oil (residual oil plus gas in solution equals reservoir oil — use differential gas-liberation data, (Fig. 2).

(a) Convert mole composition of residual oil to liquid composition (volume fraction).

(b) Plot mole composition of reservoir gas versus liberation pressure, Fig. 10.

(c) Obtain gas in solution values for each step shown in differential gas-liberation data in cu ft of gas/per cu ft of residual oil.

(d) From the figure showing mole composition of reservoir gas (B-1-b) determine average mole composition of liberated gas for each step shown in differential gas-liberation data.

(e) Convert the volume of "gas in solution" for each step into the equivalent liquid volume at 60°F in cu ft (using handbook for conversion factors).

(f) Add the equivalent liquid volume of gas in solution (B-1-e) to 1 cu ft of residual oil volume (B-1-a). (The summation of the components of the residual oil and gas in solution gives the volume of the reservoir oil at 60°F per cu ft of residual oil at 60°F.)

(g) Find the equivalent liquid composition (volume fraction) at 60°F of 1 cu ft of the reservoir oil (at reservoir temperature and pressure) by dividing the values in (B-1-f) by the "relative oil volume factor" at the companion reservoir pressure from the differential gas-liberation data.

(h) Plot the volume fraction of each hydrocarbon in the reservoir oil versus pressure (B-1-g).

(2) Liquid volumes of the produced hydrocarbons (reservoir oil plus reservoir gas equals flowing fluid).

(a) Obtain liquid composition (volume fraction) of

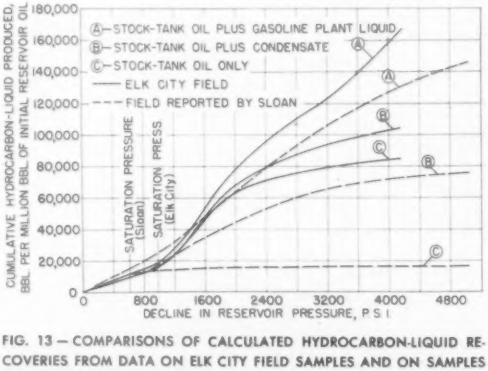

FIG. 13 — COMPARISONS OF CALCULATED HYDROCARBON-LIQUID RECOVERIES FROM DATA ON ELK CITY FIELD SAMPLES AND ON SAMPLES REPORTED BY SLOAN (USING 30 PER CENT INTERSTITIAL WATER ASSUMED).

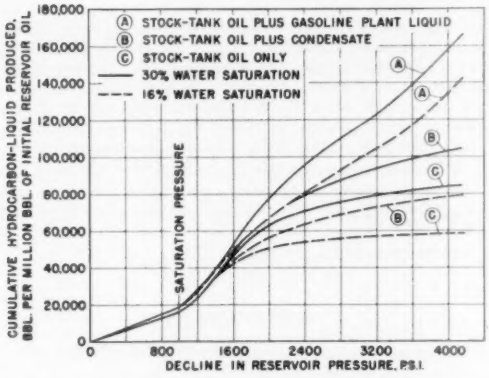

FIG. 14 — EFFECT OF INTERSTITIAL WATER CONTENT ON CALCULATED HYDROCARBON-LIQUID RECOVERIES (ELK CITY FIELD DATA).

1 cu ft of oil in reservoir for the average pressure used in each step of the material-balance calculations in "*A*" from (B-1-h.)

(b) Obtain volume of reservoir oil produced during each step from the material-balance calculations (A-4).

(c) Determine liquid volumes of the hydrocarbons in the reservoir oil produced — liquid compositions (B-2-a) times volume of reservoir oil produced (B-2-b).

(d) Calculate the equivalent liquid volume in cubic feet for each hydrocarbon component of 1 Mcf of reservoir gas from equivalent liquid volume of liberated gas (B-1-e). Plot volume versus pressure.

(e) Obtain volume of produced reservoir gas from material-balance calculations (A-4).

(f) Obtain liquid volume of each hydrocarbon component for the produced reservoir gas — (B-2-d) times Mcf of gas as obtained from (B-2-e).

(g) Obtain total liquid volume of each hydrocarbon-liquid component produced during each step — components in the produced reservoir oil (B-2-c) plus components in the produced reservoir gas (B-2-f).

(3) Mole composition of flowing fluid.

(a) Obtain data from (B-2-g) — liquid volume of components produced during period.

(b) Obtain equivalent liquid volumes of C_7 to C_{10} from handbook. Obtain equivalent liquid volume of C_7+ from molecular weight of C_7+ from oil and molecular weight of C_7+ from gas condensate.

(c) Convert from liquid composition (volume fraction) to mole composition.

(4) Total gas/hydrocarbon liquid ratio from gasoline plant.

(a) Start with (B-2-g) — liquid volume of components produced during period.

(b) Calculate the volume of gasoline-plant liquid and gas for each period.

(c) Determine average gas/hydrocarbon liquid ratio for each period.

C. Corrected Gas/Oil Ratio and Stock-Tank Liquid Volumes when Considering the Condensate from the Production of the Gas that was Liberated in the Reservoir.

(1) Determine the volume of condensate obtainable from the produced gas that has been liberated in the reservoir and the produced gas/hydrocarbon liquid ratio.

(a) Refer to curves showing mole composition of reservoir gas versus reservoir pressure (B-1-b).

(b) Use "*K*" constants and calculate total gas/hydrocarbon liquid ratios for several reservoir pressures; construct curve. Also, calculate composition of the liquid and the gas phases.

(c) Using (C-1-b), determine gas/hydrocarbon liquid ratios for pressures that are average for the various periods used in material-balance calculations.

(d) Divide reservoir gas production (A-4) for period by (C-1-c) to obtain condensate produced during period.

(2) Determine the volume of stock-tank hydrocarbon liquid produced and the corrected gas/hydrocarbon liquid ratio for each material-balance step.

(a) Determine the total stock-tank hydrocarbon liquid produced by adding the volume of condensate (C-1-d) to the volume of oil (A-4).

(b) Calculate the equivalent gas-vapor volume for 1 cu ft of condensate (use composition of stock-tank hydrocarbon liquid as obtained by "*K*" constants calculated on the reservoir gas (C-1-b) at an intermediate pressure, 2,400 psia).

(c) Multiply (C-2-b) by condensate produced durin period (C-1-d).

(d) Subtract (C-2-c) from gas produced (A-4) to obtain the corrected volume of gas produced.

(e) Calculate corrected gas/oil ratio and cumulative stock-tank liquid produced from (C-2-a) and (C-2-d).

D. Additional Calculations.

(1) Liberated gas in the reservoir

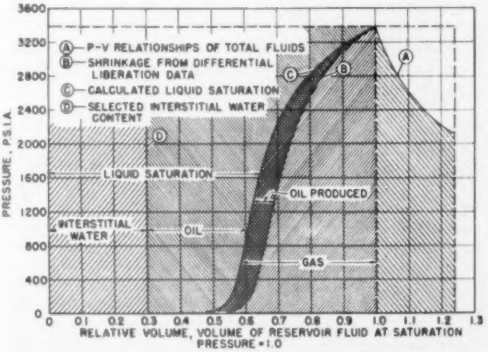

FIG. 15 — RESERVOIR PERFORMANCE INDICATED BY DATA FROM THE ELK CITY FIELD SAMPLES.

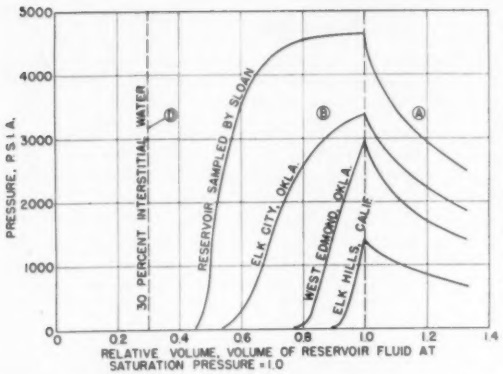

FIG. 16 — COMPARISON OF PHYSICAL PROPERTIES OF RESERVOIR FLUIDS FROM FOUR FIELDS.

(a) Obtain liquid saturation in reservoir from (A-3).

(b) Obtain gas saturation in reservoir, 1 minus the liquid saturation (D-1-a).

(c) Number of cubic feet of gas in reservoir at reservoir pressure and temperature equals the volume of reservoir in barrels times gas saturation (D-1-b) times 5.6146.

(d) Correct the volume of gas in the reservoir (D-1-c) to standard conditions.

(e) Total gas liberated in reservoir at a designated pressure equals the volume of gas in the reservoir corrected to standard conditions (D-1-d) plus the total liberated gas produced (A-4) to the same pressure.

(2) Liquid volume of each hydrocarbon component of produced fluid.

(a) Using data on the liquid volume of each component produced (B-2-g), the liquid-volume-fraction composition of initial reservoir oil (B-1-f), and volume of initial reservoir oil, calculate percentage production of each component.

ACKNOWLEDGMENTS

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LABORATORY MEASUREMENTS OF RELATIVE PERMEABILITY

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ABSTRACT

This paper presents the results of laboratory measurements of relative permeabilities to oil and gas on small core samples of reservoir rock by five methods, and describes the influences of such factors as boundary effect, hysteresis, and rate upon these measurements. The five methods used were the "Penn State," the "single core dynamic," the "gas drive," the "stationary liquid," and the "Hassler" techniques.

In those methods in which the results are subject to error because of the boundary effect, the error may be minimized by the use of high rates of flow. In order to avoid complexities introduced by hysteresis, it is necessary to approach each saturation unidirectionally. Observed deviations of relative permeabilities with rate can be explained as a manifestation of the boundary effect, and disappear as the boundary effect vanishes.

The results indicate that all five methods yield essentially the same relative permeabilities to gas. Of the four methods applicable to the determination of relative permeability to oil, three, the Penn State, single core dynamic, and gas drive, gave relative permeabilities to oil which were in close agreement. The Hassler method gave relative permeabilities to oil which were consistently lower than the results obtained by the other methods.

INTRODUCTION

The relationship between the effective permeability of a reservoir rock to each of the fluids flowing through it and the corresponding fluid saturation is an important characteristic of the reservoir rock. Knowledge of this characteristic is extremely important in the prediction of the behavior of oil and gas reservoirs and of the ultimate recovery to be expected under various operating conditions. These effective permeabilities are usually expressed as the "relative permeability" to a fluid phase, defined as the ratio of the effective permeability to the permeability of the rock to a single phase at 100 per cent saturation.

Relative permeability-saturation relations are not the same for all kinds of reservoir rock, but may vary from formation to formation, and within the different portions of a heterogeneous formation. In studying the performance of a specific reservoir, it is necessary, then, that the relative permeability characteristics of the individual portions of the reservoir be measured. These measurements may be made in the laboratory on small core samples from the reservoir.

Various techniques have been proposed for the measurement in the laboratory of relative permeability-saturation relations. In varying degree, difficulties attend the use of all of the methods which have been proposed. It is the purpose of this paper to discuss the factors which influence the measurement of relative permeability, the difficulties encountered in several methods, and to present comparative results obtained by the use of various techniques.

FACTORS WHICH INFLUENCE THE MEASUREMENT OF RELATIVE PERMEABILITY

It is necessary that the relative permeability data measured in the laboratory yield the same relative permeability-saturation relationships that would govern the flow of fluids through the sample if it were to occupy its original position in the reservoir. Since the core sample upon which the laboratory measurements are made is not surrounded by similar core material as it was in the reservoir, an error in measuring the relative permeabilities may arise from the "boundary effect" which results from a discontinuity in capillary properties of the system at the effluent end of the core. Again, the rates of

[1]References given at end of paper.

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fluid flow used in the laboratory measurement of relative permeability may be higher than those which occur in the reservoir; this seeming lack of reproducibility of reservoir conditions has, in the past, caused some uncertainty as to the validity of applications of the laboratory results. Still another influence on the laboratory measurement of relative permeability is that of hysteresis.

These various factors are discussed in the following sections.

BOUNDARY EFFECT

Nature of the Boundary Effect

In the determination of relative permeability in the laboratory by the passage of two immiscible fluids through a core sample, there exists a discontinuity in capillary properties at the outflow end of the core. This discontinuity occurs where the fluids pass abruptly from the rock, a region of finite capillary pressure, into an open receiving vessel, where capillary pressure vanishes. Because of the capillary forces existing within the core, the rock tends to retain the wetting phase at the outflow end. This results in an accumulation of the wetting phase, so that the saturation of that phase at the outflow boundary is maintained at a higher level than throughout the remainder of the core.

Various investigators[1,2,3] have observed and discussed this "boundary effect" in connection with their studies of relative permeability and capillary behavior. Leverett[2] observed in his experimental flow of oil and water through sands that there was a saturation gradient from a relatively high water saturation at the boundary to a lower one at a relatively large distance from the boundary.

Influence of the Boundary Effect on Relative Permeability Measurements

Where a saturation gradient, such as that due to the boundary effect, exists in a core sample, the actual pressure drop across the core which is effective in causing flow of the wetting phase is less than that causing flow of the non-wetting phase by an amount equal to the difference in capillary pressure at the two ends of the core. If this fact be disregarded, and the pressure drop in the wetting phase be assumed to be that in the non-wetting phase, it is evident that the relative permeability to the wetting phase computed by use of this assumption is too low.

Another possible disturbing influence of the boundary effect on the measurement of relative permeability results from the existence of a saturation gradient. Where such a gradient exists, the relative permeabilities to both phases flowing vary throughout the core with changes in the saturation. If these variations be disregarded, and reliance be placed on the gross measurements made on a core in which there is a saturation gradient, the relative permeabilities to both phases at the average saturation are too low. Any error from this source is superimposed upon that resulting from the use of a spurious pressure drop in the wetting phase.

Means of Avoiding or Minimizing the Boundary Effect

Of the various ways in which the boundary effect may be avoided or minimized in the measurement of relative permeability, the most obvious is that of performing all measurements on a section of the core sample far enough removed from the outflow end to insure that the saturation gradient in the test section is insignificant. In practice, this may be done by use of a single core only with difficulty. A procedure equivalent in principle consists in placing beyond the test core a core sample of similar material. The boundary effect is then transferred to and confined within the latter core. In this procedure the two must be in capillary contact.

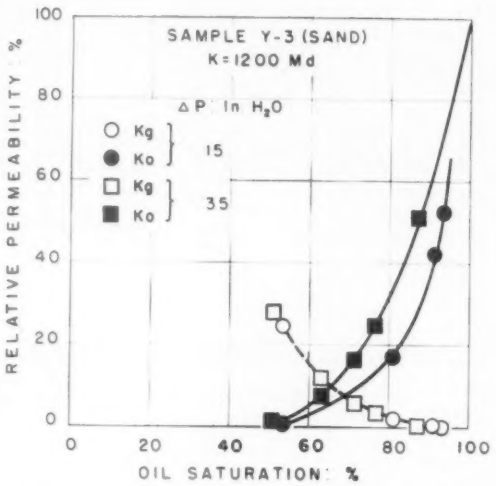

FIG. 1 — EFFECT OF PRESSURE GRADIENT ON RELATIVE PERMEABILITY (LACK OF CAPILLARY CONTACT BETWEEN CORES). PENN STATE.

The boundary effect may also be minimized by the use of high rates of flow. It may be shown by theoretical considerations based on d'Arcy's law, relative permeability-saturation relations, and capillary pressure-saturation relations that the saturation distribution along the core varies for different rates of flow. At low rates of flow the saturation gradient extends over a considerable distance from the outflow end, and at increased rates of flow the gradient extends over shorter distances. It may be concluded that at high rates of flow the error introduced by the boundary effect may be made so small that it will not appreciably affect the measurements of relative permeability.

Another method of avoiding the influence of the boundary effect on the measurement of relative permeability consists in holding the wetting phase stationary by capillary forces and flowing only the non-wetting phase.

Still another method of avoiding the boundary effect consists in maintaining a uniform saturation distribution throughout the core by controlling the capillary pressure at both ends of the core sample. This is accomplished by placing at both ends of the core discs of a material which is permeable only to the wetting phase. In this procedure both phases may be made to flow, with independent control of pressure gradient maintained in each phase.

RATE EFFECT

Some concern has been expressed in the past by various investigators over the apparent dependence of relative permeability on rate of flow used in the laboratory measurements. Since some measurements are made at high rates of flow and

others at low rates, the question arises as to whether the relative permeabilities to oil and gas are rate-sensitive in the absence of boundary effect, or whether the observed deviations in measurements in the laboratory with variations in rate of flow through the core sample are solely manifestation of the boundary effect and disappear as the boundary effect is eliminated. It is believed that the latter is correct and that there is no influence on the laboratory measurement of relative permeability exerted by the rate of flow as such in the absence of boundary effect.

HYSTERESIS EFFECT

Relative permeability-saturation relations are not unique functions of saturation for a given core, but are subject to hysteresis; that is, the relative permeability to a fluid at a given saturation depends on whether that saturation is obtained by approaching it from a higher or lower value. Since hysteresis does exist, care must be exercised that the relative permeabilities measured in the laboratory are obtained under conditions wherein each saturation is approached in the desired manner.

The type relative permeability curve that is representative of flow characteristics through the formation in the reservoir depends on the mechanism by which the reservoir is depleted. If the reservoir is depleted by decreasing the oil saturation and increasing the gas saturation, as in a dissolved-gas drive or expanding gas-cap drive, the drainage relative permeability curves should be used. If, however, the reservoir is depleted by decreasing the oil saturation and increasing the water (or wetting phase) saturation, as in a water-drive mechanism, the imbibition relative permeability curves apply.

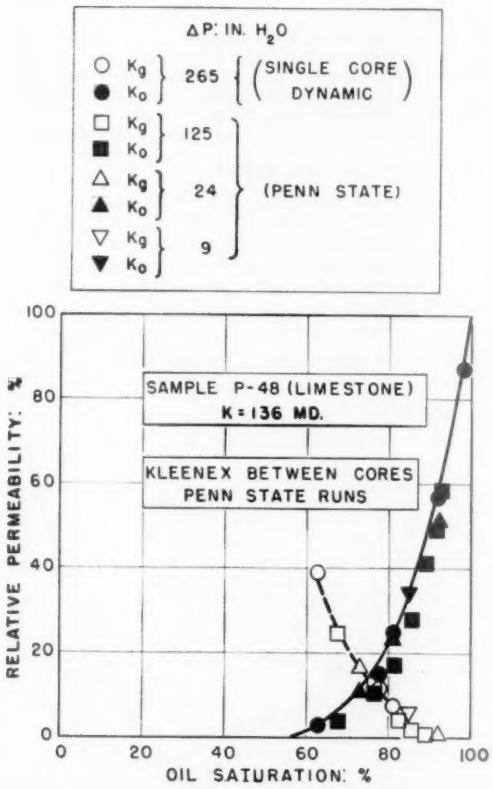

FIG. 2 — EFFECT OF PRESSURE GRADIENT ON RELATIVE PERMEABILITY (CAPILLARY CONTACT BETWEEN CORES). PENN STATE.

PROCEDURES AND RESULTS OF RELATIVE PERMEABILITY MEASUREMENTS

Five procedures for the measurement of relative permeability have been investigated in the work described in following sections. In these techniques the influence of the boundary effect has been avoided or minimized in various ways. Throughout all these investigations, a two-phase system, oil and gas, was used.

Core Samples Used

The core samples used were all from the producing intervals of various reservoirs. Both sandstone and limestone samples were employed. Common to all methods was the preparation of the core samples. These samples, short cylinders ⅞-in. in diameter, were cut from well cores parallel to the bedding planes. After extraction with carbon tetrachloride, they were mounted in Lucite cylinders with an outside diameter of 1½ in. The end of the samples and of the surrounding plastic were faced, and a small concentric groove was cut in one end at the junction of the rock and Lucite. Access to this groove, a piezometer ring, was provided by a small hole drilled into it through the Lucite.

Penn State Method

The Penn State[6] method, so-called because it was devised at Pennsylvania State College, attempts to avoid the influence of the boundary effect by use of a test core sample between two samples of similar material, the three being in capillary contact. In theory, the boundary effect may thus be confined to the downstream sample, with no saturation gradient existing in the sample under test. The purpose of the upstream core is to act as a mixing section for the two fluid phases.

Relative permeabilities were measured by the Penn State method by use of kerosene and helium as the two fluid phases. The cores were first saturated with the oil, and then oil was allowed to flow through them at a rate that gave a predetermined pressure drop. The gas was then allowed to flow at a very low rate. After the system had reached equilibrium, the test core was removed quickly, and the oil saturation was determined by weighing. The core sections were then reassembled, and flow of both phases was resumed at the

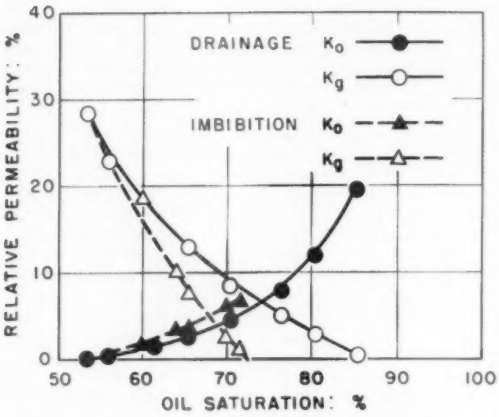

FIG. 3 — HYSTERESIS — RELATIVE PERMEABILITY. PENN STATE.

rates which had existed previously. The rate of flow of the oil phase was then decreased slightly, and the rate of flow of the gas was increased simultaneously to maintain the pressure drop across the core at its previous value. After equilibrium had again been attained, the test section was removed and the saturation was determined. This stepwise procedure was repeated until a complete relative permeability curve had been obtained at incremental changes in the fluid saturation.

Much difficulty was encountered initially in relative permeability measurements by the Penn State apparatus when the flow rate was varied over wide limits. In early experiments, the kerosene was presaturated with gas at the pressure at which the kerosene was introduced into the apparatus. With saturated kerosene as the wetting phase, it was observed that the measured relative permeabilities to both oil and gas were erratic. When experiments were conducted with kerosene from which most of the dissolved gases had been removed, the erratic deviations disappeared. A degassed oil phase was accordingly used in all subsequent work.

Another difficulty observed with the Penn State technique was that due to a boundary effect. Although, in theory, the Penn State technique should give results that are free from boundary effect errors, it was observed that the saturation gradient was not always eliminated from the test sample because capillary contact did not always exist between the test sample and the end sample, or "boundary effect absorber." This was particularly true in the case of samples that were loosely consolidated. The lack of capillary contact between cores caused the relative permeability-saturation relationships to appear to be a function of the applied pressure gradient or flow rate. This variation with pressure gradient was more pronounced in the oil curve than in the gas curve, since the measured pressure drop across the test section was not the actual pressure drop effective in causing flow of the oil.

Fig. 1 shows the increase with pressure gradient of relative permeabilities measured with poor capillary contact between the core samples. Although in this illustration there is shown practically no variation in the relative permeability to gas with increase in pressure gradient, similar tests on other cores did indicate a small variation. Deviations of the type illustrated by Fig. 1 may be expected to result from boundary effect errors if good capillary contact does not exist between the tested core and the boundary absorption core.

Fig. 2 illustrates results of determinations in which good capillary contact between cores appeared to be achieved. The cores used in these determinations were limestone, so that the faces remained flat and true under repeated tests. Layers of Kleenex were placed upon the cores to insure capillary contact. The relative permeabilities were in this case independent of pressure gradient over a wide range, even though the pressure drop across the core was varied from 9 to 125 in. of water. One point obtained with a pressure drop across the core of only 9 in. of water agreed quite well with measurements obtained under conditions of much higher pressure drop. This point also agreed with measurements obtained by another method, the single core dynamic method, at a pressure drop of 265 in. of water.

The effects of hysteresis in measurements made by the Penn State method are illustrated in Fig. 3. In this figure the solid curves, which are drainage curves, were obtained by starting with the sample at 100 per cent oil saturation and progressively decreasing the saturation to a value of 53 per cent. The dashed curves, which are imbibition curves, were obtained by then increasing the oil saturation. If, instead of starting the imbibition curve at a saturation of 53 per cent, the imbibition run were started at an oil saturation of zero, the relative permeability to gas would have been lower than that shown by the curve in Fig. 3, and would have reached zero at a lower oil saturation. The relative permeability to oil would have been increased correspondingly.

Single Core Dynamic Method

In this method the boundary effect is minimized by the use of a rate of fluid flow which is high enough to make insignificant the effects of the saturation gradient in the short test core.

The equipment used in this method was similar to that employed in the Penn State technique, except that a single core, mounted in Lucite, was used. The oil and gas phases were

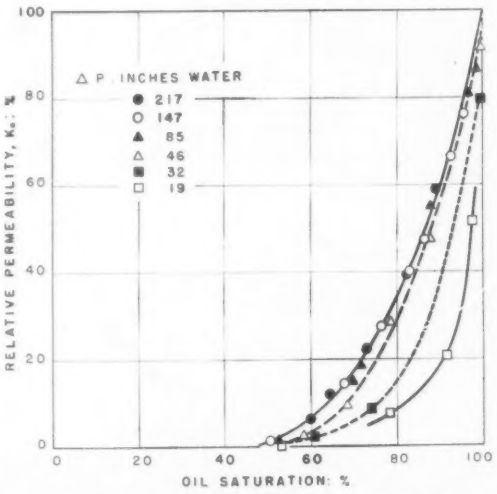

FIG. 4 — RATE EFFECT — RELATIVE PERMEABILITY. SINGLE CORE DYNAMIC.

introduced directly into the core from a feed head. No boundary effect absorber was used.

In making determinations by this method, the core sample was initially saturated completely with the oil phase. A rate of flow of the oil was then established which would correspond to a predetermined pressure drop across the core. Helium was then admitted to the core at a low rate. After equilibrium had been established, the oil saturation was determined by weighing. Successively higher gas flow rates, and correspondingly lower oil rates were employed in succeeding steps to determine complete relative permeability-saturation relations.

It was found that at low rates of fluid flow the measured relative permeability to oil varied with the flow rate. When a sufficiently high rate of flow was attained, however, this variation disappeared, and the relative permeability became independent of flow rate. This effect is illustrated in Fig. 4, which portrays results obtained on a sand core of high permeability. The core sample was approximately an inch long. Kerosene was used as the liquid phase.

In Fig. 4, it may be observed that the measured relative permeability to oil increased with increasing pressure drop until the pressure drop attained a value of about 85 in. of water. Thereafter, further increases in pressure gradient, or flow rate, caused no change in the relative permeability. The gas curve, not shown in this illustration, was the same for all pressure differences except for the lowest value of 19 in. of water, which gave slightly depressed values of the relative permeability to gas.

In order to investigate the effect of change of rate of flow on measurements made by this technique, without introducing possible complications due to change in pressure drop, a series of measurements was made with oils of various viscosities, flowing under an essentially constant pressure gradient. In these runs the viscosities of the oils ranged from 1.8 to 25 centipoises.

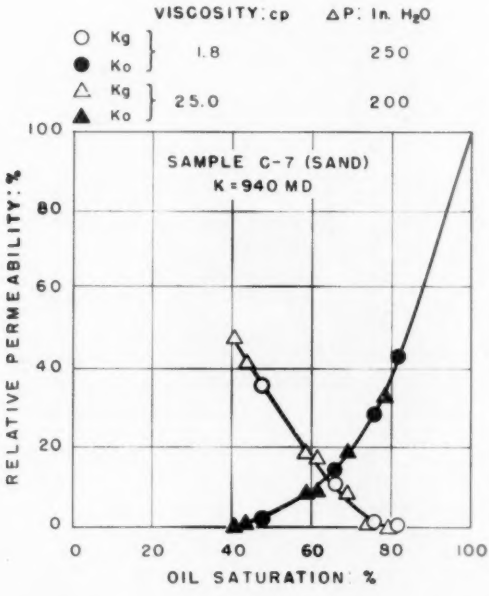

FIG. 5 — EFFECT OF OIL VISCOSITY ON RELATIVE PERMEABILITY. SINGLE CORE DYNAMIC.

Results typical of these determinations are shown in Fig. 5. In the case illustrated, the pressure drop was maintained high enough to render insignificant the error due to the boundary effect. It is apparent from Fig. 5 that a fourteenfold difference in rate of flow had no effect on the relative permeability-saturation relations.

The results illustrated in Figs. 4 and 5 show that relative permeability is not a function of rate of flow in the absence of boundary effects.

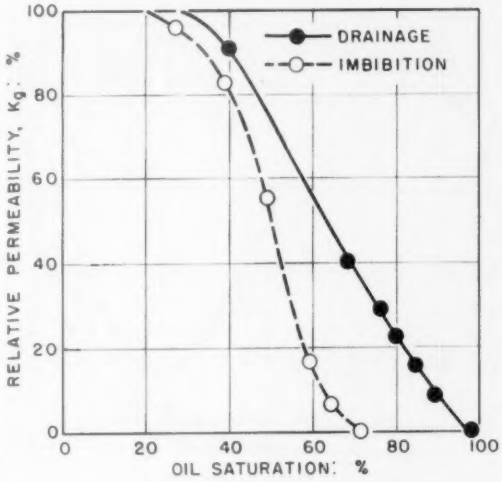

FIG. 6 — HYSTERESIS — RELATIVE PERMEABILITY. STATIONARY-LIQUID.

Stationary Liquid Method

In the stationary liquid method,[5] the boundary effect is avoided by holding the wetting phase stationary within the core by capillary forces. Only the non-wetting phase is permitted to flow. This is accomplished by the use of a very low pressure gradient across the core. The method is applicable only to the determination of relative permeability to the non-wetting phase.

In the use of this method, relative permeability-saturation curves for gas were obtained by starting with the core completely saturated with oil. The oil saturation was then reduced by blotting the core with Kleenex. When the oil saturation was reduced to less than that corresponding to the equilibrium gas saturation, gas was passed upward through the core under a pressure drop of 1 in. of water. The relative permeability to gas at that point was measured, and the oil saturation was determined by weighing. This process was repeated until the complete relation of the gas relative permeability to saturation was obtained.

It was thought possible that blotting the ends of the sample with Kleenex and determining the relative permeability im-

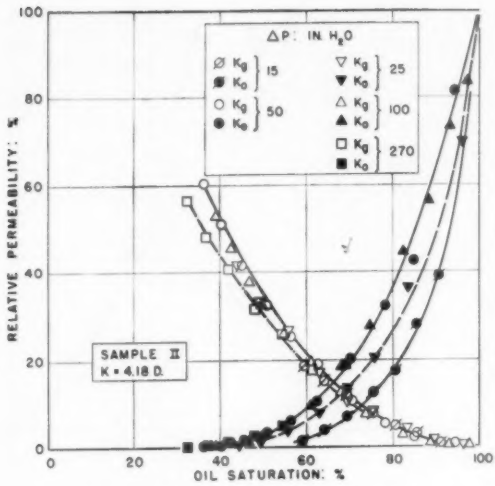

FIG. 7 — RELATIVE PERMEABILITY — GAS DRIVE.

mediately might not give the oil within the core sufficient time to arrange itself into its true drainage distribution. An experiment was accordingly conducted in which the sample was blotted with Kleenex and was then allowed to stand 24 hours before the relative permeability to gas was determined. The relative permeability curves were identical in the two cases.

Other experiments were conducted to determine whether or not the manner in which the oil saturation of the core was reduced affected the relative permeability-to-gas curves. To check this, in addition to blotting the core with Kleenex, the oil saturation in the sample was reduced by two other means. One method was to desaturate the sample by displacing the oil with gas in a porous diaphragm cell. Another method used to desaturate the core was to place the sample in the Penn State apparatus and to continue flow until equilibrium was reached. The sample was then removed from the Penn State apparatus and the relative permeability to gas was measured in the stationary liquid apparatus. The relative permeabilities to gas in all three cases gave identical curves. On the basis of these findings, it was considered satisfactory to determine the gas permeability immediately after desaturation by blotting with Kleenex.

Although the manner in which the core was desaturated apparently had no effect on the determination of gas permeability, it was found that a core which had been desaturated and then allowed to imbibe oil exhibited a marked hysteresis effect. This effect is shown in Fig. 6. In obtaining the results illustrated in Fig. 6, the drainage curve was determined by the ordinary stationary liquid technique. The oil saturation was then reduced to zero by drying, and the core was then allowed to imbibe oil in incremental steps. The relative permeability to gas was determined at each step. The hysteresis effect shown in Fig. 6 is apparently the same as that which has been observed in determinations made by the Penn State method.

A limited number of gas relative permeability-saturation relationships were determined with the sample containing, in addition to the oil, a low brine saturation corresponding to connate water. The investigation showed that the presence of the brine had no effect on the relative permeability to gas.

For a number of cores the oil saturation was reduced until the relative permeability to gas was either 100 per cent or very close to it. Capillary pressure curves were determined for some of these cores, so that the "irreducible minimum" saturations were known. In all such cases the relative permeability to gas reached 100 per cent at oil saturations greater than the irreducible minimum saturations.

Gas Drive Method

In this method the influence of the boundary effect is minimized by the use of a high rate of flow. The method differs from the stationary liquid method in that both phases flow simultaneously; it differs from the single core dynamic method in that only gas is admitted to the core. The flow of both phases results from the displacement of portions of the oil by the flowing gas: hence, the name, "gas drive." This method was first suggested by Hassler[4] in 1936.

In making measurements by the use of this method, the core was first saturated with a high viscosity (19 centipoises) oil. An oil with a relatively high viscosity was chosen so that it would be forced out of the core slowly, thereby increasing the accuracy with which relative permeability could be measured.

Gas at a predetermined pressure was forced through the core for 5 seconds, and the volume of gas flowing during this

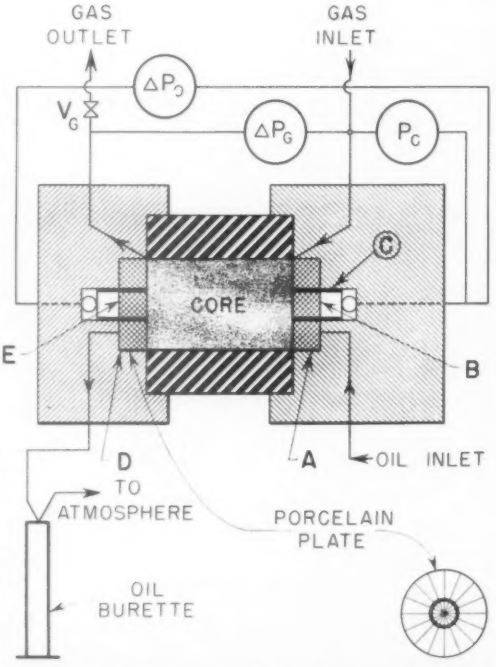

FIG. 8 — RELATIVE PERMEABILITY APPARATUS (HASSLER'S PRINCIPLE).

period was measured. The oil saturation in the core was then determined by weighing. The core was again subjected to gas flow for another short interval of time, and the reduced saturation was determined. The procedure was repeated until completed relative permeability-saturation relations were obtained.

The manner in which the relative permeability varied with the pressure across the sample was similar to that observed in the single core dynamic method. This is illustrated by Fig. 7, which shows typical results obtained by the gas drive method under different pressure gradients. It may be observed that the relative permeability to oil increased with incerasing pressure drop until a pressure drop of about 50 in. of water was attained. Thereafter increase of pressure gradient had no further effect on the relative permeability to oil.

No significant change of relative permeability to gas appeared to result from increasing pressure gradient until a pressure drop of 270 in. of water was used. At this high pressure gradient the relative permeability to gas was decreased. This deviation was probably due to inertial effects encountered at high rates of gas flow.

Hassler Method

The boundary effect is avoided in the Hassler method[7] by controlling and making equal the capillary pressure at both ends of the core. This is accomplished by placing the core between two discs permeable only to the wetting phase. This permits a uniform saturation to be maintained throughout the length of the core, even at low rates of flow.

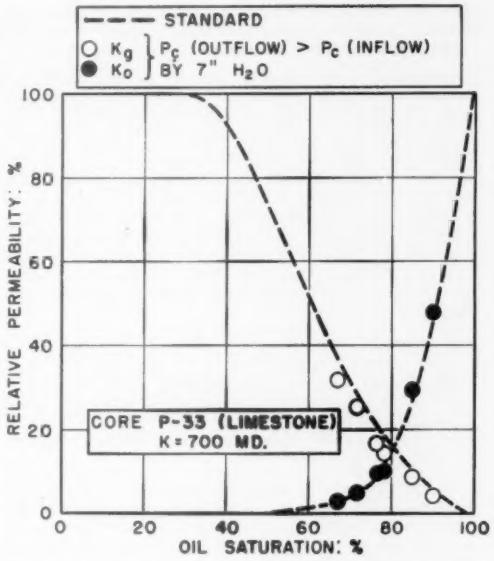

FIG. 10 — EFFECT OF CAPILLARY PRESSURE GRADIENT, HASSLER TECHNIQUE.

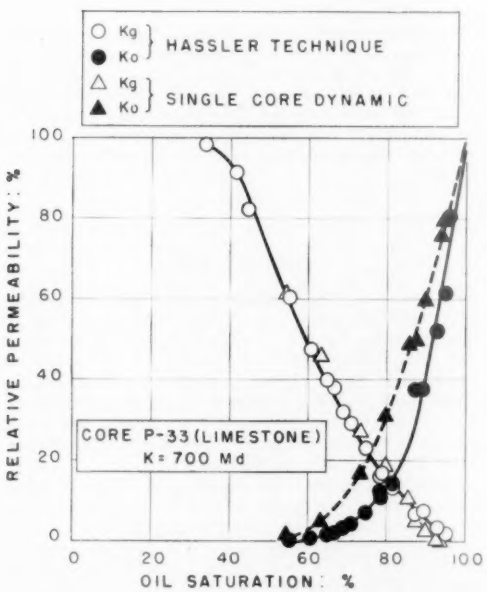

FIG. 9 — RELATIVE PERMEABILITY, HASSLER TECHNIQUE.

The apparatus for measurements made by the Hassler method is shown in Fig. 8. The semi-permeable discs at each end of the core allow oil, but not gas, to pass. They also permit the pressure drop in the oil phase to be measured independently of that in the gas phase.

In the measurement of relative permeability, the sample to be tested was saturated with oil, and then was placed in the apparatus with a few layers of Kleenex at both ends to insure good contact between the core and semi-permeable discs. Oil entered the core through disc *A*. Disc *A* was isolated from the small disc *B* by the metal sleeve *C*. The pressure in the oil at the inflow end was measured through the disc *B*. Gas entered the core through radial grooves in the face of disc *A*. The difference between the pressure in the oil and in the gas at the inflow end is the capillary pressure and was measured by the gauge *P*..

The oil and gas passed through the sample at rates such that the pressure drop in the two phases across the core was the same. This was accomplished by adjusting valve V_g, which controlled the rate of flow of gas through the sample, so that the pressure drop in the gas phase was equal to the pressure drop in the oil phase. This was done so that the capillary pressure at the outflow end would be equal to the capillary pressure at the inflow end. The gas left the core through radial grooves in disc *D*, and the pressure of the oil at the outflow end was measured through disc *E*. After equilibrium was reached, the sample was removed and the saturation of the sample was determined by weighing.

Typical results obtained by the Hassler method are shown in Fig. 9. In this illustration are also shown curves obtained on the same limestone core by the single core dynamic method.

It is evident from these data that the Hassler results on permeability to oil were lower than those obtained by the other method. The gas curves were in good agreement .

Ordinarily, a depression of the oil relative permeability curve would suggest the presence of a saturation gradient. To investigate experimentally the apparent depression of the oil curve shown in Fig. 9, an experiment was performed in which a saturation gradient was deliberately imposed across the core. To this end, the capillary pressure at the outflow end was made about 7 in. of water higher than the capillary pressure at the inflow end. The results that were obtained are shown in Fig. 10, compared with the results obtained when no saturation gradient was presumed to exist. The oil curves of Figs. 9 and 10 were nearly identical. The gas curve obtained by imposition of the saturation gradient was depressed only slightly.

Relative permeability measurements made with a higher capillary pressure at the inflow end than at the outflow end again gave an oil relative permeability curve that was the same as the curve of Fig. 9, and a gas relative permeability curve that was depressed slightly. The foregoing experiments failed to provide an explanation of the apparent depression of the oil curve of Fig. 9.

By use of the same core employed in the above determinations, an investigation was conducted to determine the characteristics of relative permeability curves obtained with oil and gas flowing in opposite directions within the same core. The procedure for this run was the same as for an ordinary run, except that the gas inlet and outlet were interchanged. The pressure drop in each of the phases was adjusted to about 2 in. water to keep the saturation gradient within the core to a minimum. The results of this experiment are shown in Fig. 11, and are seen to agree with the relative permeability curves obtained in the usual manner. The accuracy of the measurements in this investigation were not as great as in a normal run because of the lower pressure drops that were used for the two phases. The results indicated that the relative permeability curves were the same whether the two phases flowed concurrently or in opposition.

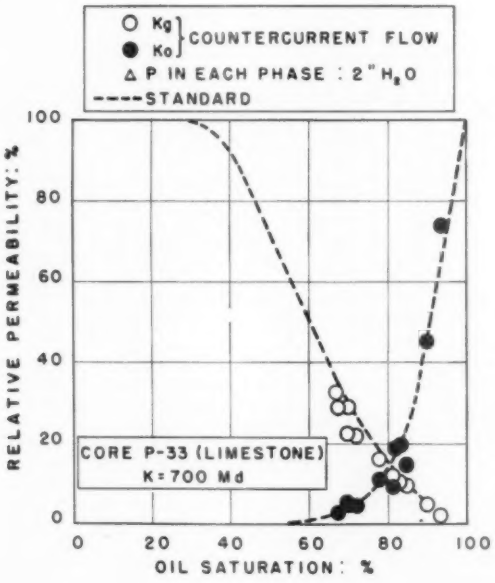

FIG. 11 — EFFECT OF COUNTERCURRENT FLOW, HASSLER TECHNIQUE.

COMPARISON OF RESULTS

The Penn State, the single core dynamic, the gas drive, and the Hassler techniques gave the same curves for relative permeability to gas, as shown in Figs. 12 and 13. The stationary liquid method in some cases gave curves for relative permeability to gas which were in good agreement with those obtained by the other methods. In general, however, the relative permeability to gas determined by the stationary liquid technique was lower than that by the other methods in the region of the equilibrium gas saturation. This resulted in an equilibrium gas saturation which was greater than the value obtained by the other methods.

Measurements of the relative permeability to oil made by the single core dynamic, the Penn State, and the gas drive methods gave the same results except in the regions of high oil saturation, where the values obtained by the gas drive technique were sometimes high. The relative permeability to oil measured by the Hassler method gave results which were lower than those obtained by the other three methods. Comparisons of the results of the different methods may be seen in Figs. 9, 12, and 13.

The Hassler technique is the slowest of all the methods for measuring relative permeability, requiring about one week per sample. The gas drive technique is the fastest, requiring only about an hour for running the complete relative permeability curves. One or two cores can be analyzed a day by means of the single core dynamic or the Penn State techniques. About four cores can be analyzed a day by the stationary liquid technique.

CONCLUSIONS

1. In those methods of determination of relative permeability in which the results are subject to error because of the boundary effect, the error may be minimized by the use of high rates of flow.

2. No variation of relative permeability with variation of rate in the absence of boundary effects has been found. Deviations of relative permeability with rate have been observed only where boundary effects are known to exist, and disappear as the boundary effect vanishes.

3. Hysteresis exists in the measurement of relative permeability. Since relative permeability is not a unique function of saturation because of hysteresis, care must be exercised that relative permeabilities measured in the laboratory are obtained under conditions wherein each saturation is approached in the desired manner.

4. The results of measurements by the Penn State, single core dynamic, stationary liquid, gas drive, and Hassler methods indicate that all yield essentially the same values of relative permeability to gas except in the region of the equilibrium

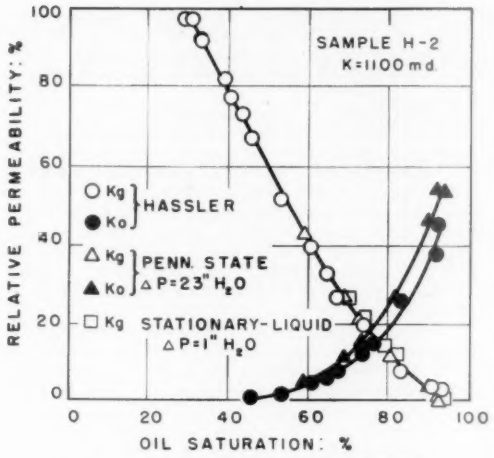

FIG. 12 — RELATIVE PERMEABILITY — THREE METHODS.

gas saturation, where the values given by the stationary liquid method are generally lower.

5. Of the methods applicable to the determination of relative permeability to oil, three, the Penn State, single core dynamic, and gas drive, give relative permeabilities which are in close agreement. The Hassler method to date has given relative permeabilities to oil which have been consistently lower than results obtained by the other methods. The reason for this difference has not been explained.

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DISCUSSION

By V. A. Josendal and B. B. Sandiford, Union Oil Co. of California, Wilmington, Calif.

The authors are to be commended for attacking the problem of laboratory measurements of relative permeability on so broad a front. It is remarkable that essentially the same curves can be obtained by so many different methods.

However, even though the authors have obtained similar relative permeability curves by five different methods, it is possible that some of their measurements may include reproducible errors. In particular their method of obtaining saturations may be faulty. It has been found in Union Oil Co. laboratories in work with the Penn State method that saturations could not be obtained accurately by weighing in either the two-phase liquid system or in particular in the gas-liquid system. If gas is present, reduction of the pressure to atmospheric before weighing causes the gas to expand and an unknown amount of fluid is forced out of the core. Another possible source of error arises from water absorption by the Lucite.

The different relative permeability to oil values obtained by the Hassler method as compared to the other three applicable methods is disturbing. Only one curve can apply in the reservoir for a given set of conditions. However, it is not certain from the data presented whether the observed difference is caused by errors in technique or actually represents different flow and fluid displacement mechanisms.

This difference could be checked by using more accurate techniques in comparing the Hassler method with one of the other three. The Penn State method might well be chosen for this comparison as it appears to be the only one of the three in which uniform saturation conditions can be established. An attempt should be made to minimize nonuniformity of saturation and all possible errors in saturation measurement and pressure measurement. In the Hassler method the pressure taps should be placed on the side of the core so

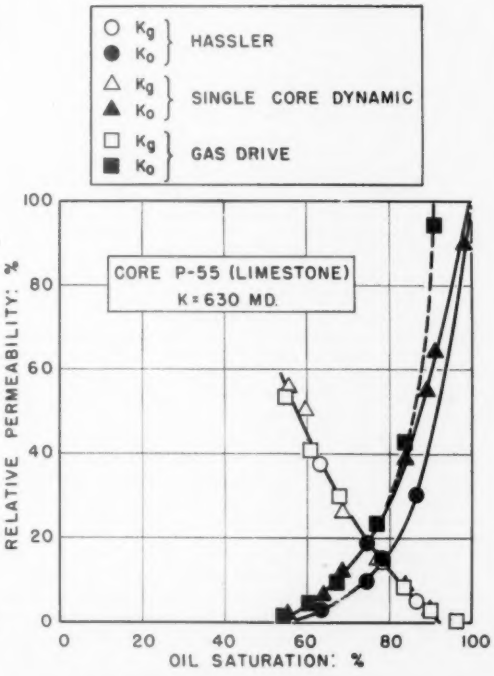

FIG. 13 — RELATIVE PERMEABILITY — THREE METHODS.

that each tap measures the true pressure over the cross section of the core, unappreciably affected by any non-parallel flow. The Penn State method could be modified so that a single long core is used, obviating the need for reliance on capillary contact between sections. In each method effort should be made to replace weighing by some improved technique for saturations.

AUTHOR'S REPLY TO V. A. JOSENDAL AND B. B. SANDIFORD

The authors believe that the measurement of saturation by weighing is sufficiently accurate for use in relative permeability determinations at the pressures used. Theoretical calculations using the gas-oil ratio, viscosity, and saturation show that the quantity of oil that may be forced from a core by the expansion of gas is very small. Furthermore, specific experiments were conducted in which a partially saturated core was placed in a chamber under gas pressure and the pressure instantaneously reduced to atmospheric. No oil was forced out of the core due to the expansion of gas within the pore space.

A special plastic having negligible water absorption is substituted for the Lucite mounting material in the experimental techniques in which water is one of the liquids present.

The authors recognize that the relative permeability to oil obtained by the Hassler technique is lower than those obtained by the other methods. These differences have been consistently present in a large number of very accurate comparisons, of which only a few of the representative curves are shown in the paper. No definite conclusions have been reached as to the possibility of different flow or fluid displacement mechanisms.

This paper does not attempt to recommend a specific method for general use, but rather to point out the progress made and the correlations obtained in the various laboratory methods of relative permeability measurement. ★ ★ ★

INTERFACIAL TENSIONS AT RESERVOIR PRESSURES AND TEMPERATURES; APPARATUS AND THE WATER-METHANE SYSTEM

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ABSTRACT

An apparatus for the determination of fluid-fluid interfacial tension by the pendant drop method has been constructed. The apparatus is refined beyond those previously described in that the samples are introduced into an evacuated windowed cell without contacting air or mercury.

Interfacial tension data are reported for the water-methane system between 74 and 280°F and 15 and 15,000 psi.

The variation of wettability of the stainless-steel dropper tip with pressure and temperature was observed incidentally to the measurements.

INTRODUCTION

The most refined previous apparatus for the determination of fluid-fluid interfacial tension at reservoir conditions was built by Hauser and Michaels.[1] These authors used the pendant drop method, previously investigated by Andreas, Hauser, and Tucker.[2] Recently, Fordham[3] has made the pendant drop method an absolute one by numerical integration of the differential equation of drop shape. It is necessary to know the difference in density of the two fluids and the acceleration due to gravity in order to evaluate the interfacial tension from measurements of drop dimensions. Contact angle is not involved in the measurements by this method.

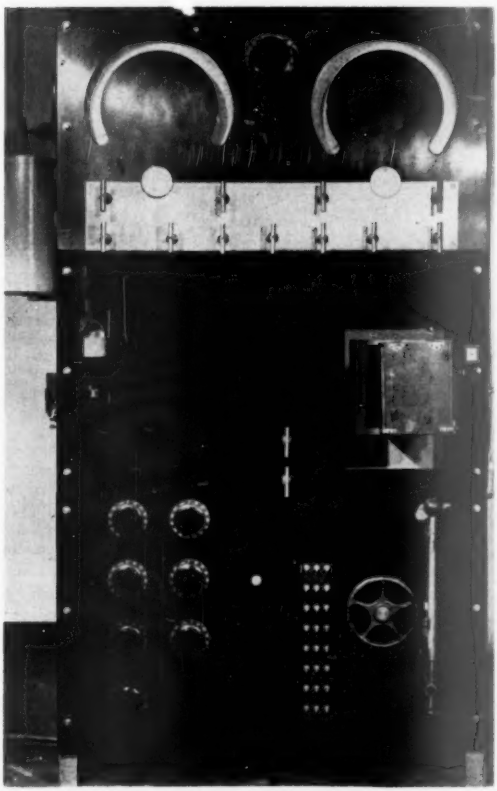

FIG. 1 — FRONT VIEW OF APPARATUS.

Some precise tests of the method have been made at atmospheric pressure and 77°F by Douglas,[4] who found agreement with established values to within about 0.1 per cent for water and air, cyclohexane and air, benzene and air, and benzene and water. No values of interfacial tension from the recent pendant drop apparatus[1] have been published by Hauser and Michaels. However, values for the water-benzene and water-decane systems are given in Michaels' thesis[5] for pressures from 15 to 10,000 psi and temperatures from 73 to 268°F. Some determinations on gas-oil and gas-water systems in the range of 15 to 4,000 psi and 78 to 178°F have been made by Hocott,[6] by the drop-volume method. The capillary rise method has been used to investigate the interfacial tension in gas-oil systems at 88°F to several thousand psi by Swartz.[7] Other determinations in gas-oil systems at pressures under 1,000 psia have been made by Jones,[8] and Beecher and Parkhurst.[9] The scarcity of data for pressures above 5,000 psi is apparent.

APPARATUS

An assembly drawing of the working section of the interfacial tension apparatus is given in Fig. 2. The pendant drop (A) is housed in a pressure chamber having glass windows (B). An agitator (C) is provided. The metal parts of the apparatus coming into contact with the sample are made of AISI Type 316 steel. Drain grooves are provided around the windows so that the sample in contact with the O-rings is not returned to the working section when the pressure is reduced.

A schematic arrangement of the apparatus is given in Fig. 3. The working section containing the pendant drop (A) is filled by samples from bombs (B) with the aid of the vacuum system (C). The O-ring sealed pistons (D) used to separate the sample from the hydraulic fluid are shown together with the pressure production and measurement system (E).

A front view of the apparatus is shown in Fig. 1. Most of the hydraulic system is at the top of the panel. The pump and displacement piston are at the lower right. The Variacs for the air bath heaters, the camera, and the vacuum gauge are also visible on the panel. The working section together with a window closure and a drop-forming tip closure are shown in Fig. 9. The carbon arc light source with filter is visible in the upper part of the picture. Two sides of the air bath with the impeller and a part of the convection shield can also be seen. The assembled air bath is shown in Fig. 10.

[1]References given at end of paper.

Manuscript received in the office of the Petroleum Branch September 14, 1950. Paper presented at the Petroleum Branch Fall Meeting in New Orleans, La., Oct. 4-6, 1950.

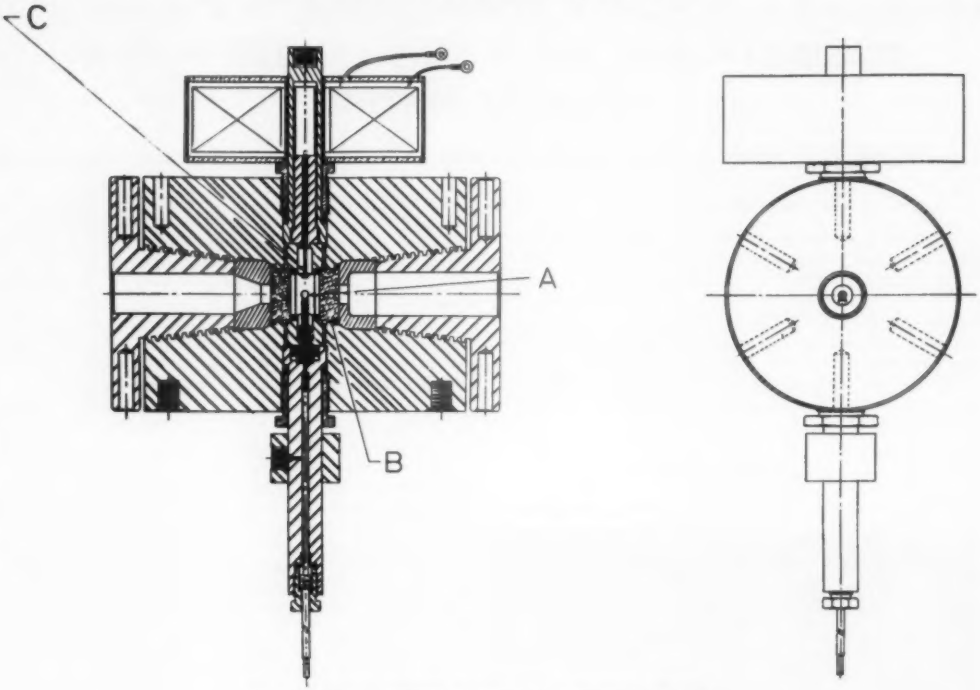

FIG. 2 — WORKING SECTION OF INTERFACIAL TENSION APPARATUS.

A part of the camera is visible in the foreground. The parts for a cylinder containing an O-ring sealed piston are on top of the air bath. The valves for the sample-introduction system are at the top of the picture.

MATERIALS

Distilled water having a resistivity of about 0.3 x 10^6 ohm cm was used. Pure grade methane obtained from the Phillips Petroleum Co. was used without further purification. This material contains 0.995 mole fraction methane. Cleaning solution was employed in the final cleaning of all parts of the apparatus which would, at any time, come into contact with the samples.

EXPERIMENTAL RESULTS

Water-Methane Interfacial Tensions

The results of the interfacial tension measurements for the water-methane system are given in Figs. 4 and 5 and in Table I. These results were obtained for 15-second-old drops, having diameters of about 0.08 in., formed on a tip having a diameter of 0.0472 in. For pressures below about 5,000 psia, or temperatures below about 160°F, the reproducibility of a given measurement is less than 1 dyne/cm. Under these conditions, the effects of pressure hysteresis, which are shown but not explained in Fig. 4 and Fig. 5, were as much as several times this value. The reproducibility at the highest temperature (280°F) and pressure (15,000 psia) encountered is estimated to be 2 dynes/cm., and the effect of pressure hysteresis is probably several times this value. No attempt has been made to explain the general shape of the isotherms or isobars because of the scarcity of thermodynamic data for the water-methane system.

The variation of interfacial tension with drop age at the lowest and highest pressures on the 100° and 280°F isotherms is portrayed in Fig. 6. In general, a maximum value is present for times under about two minutes. Density data for water and methane were taken from the literature.[9,11,12]

Wettability Changes

An interesting variation of the wettability of stainless steel samples with pressure and temperature was noticed incidentally to the determinations of interfacial tension. For example at 215.4°F and 1,005 psi, one AISI Type 316 steel dropper tip was wetted preferentially by the water in the drop as can be seen from Fig. 7A. When the pressure was increased to

Table I — Smoothed Values of Interfacial Tension in the Water-Methane System

Temp (°F)	74	100	160	220	280
Press (psia)		Interfacial Tension (dynes/cm)			
15	75.5	70	63.5	57.3*	52.8*
1,000	67	60	55.5	50.7	46.3
5,000	53.0	23	24.7	24.5	21.3
10,000	48.6	22	26	28	25.5
15,000	46.5	26	30	31	30.5

*Extrapolated value.

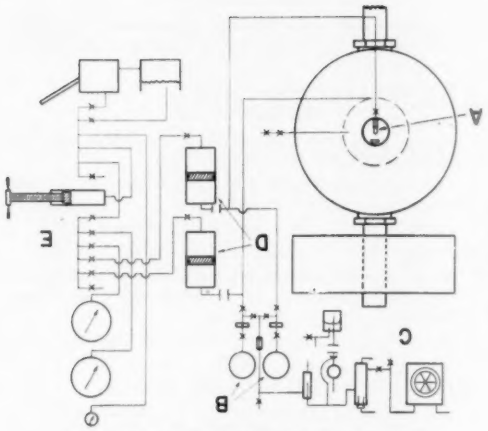

FIG. 3 — SCHEMATIC ARRANGEMENT OF APPARATUS.

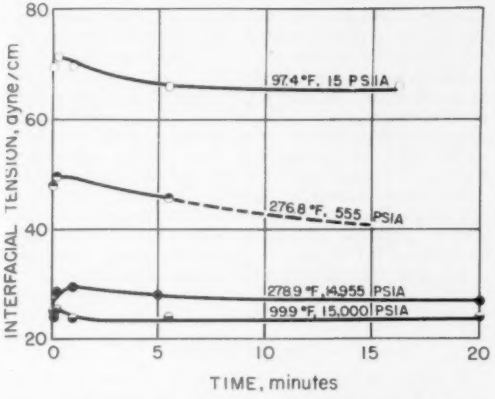

FIG. 6 — VARIATION OF INTERFACIAL TENSION WITH DROP AGE.

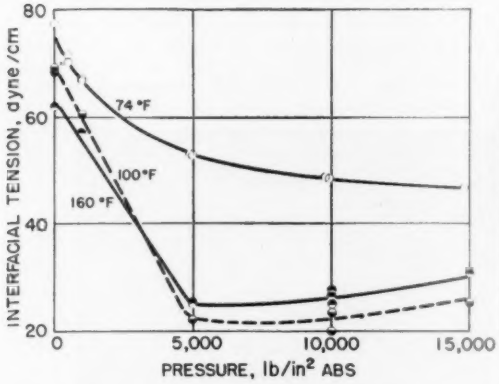

FIG. 4 — INTERFACIAL TENSION IN THE WATER-METHANE SYSTEM.

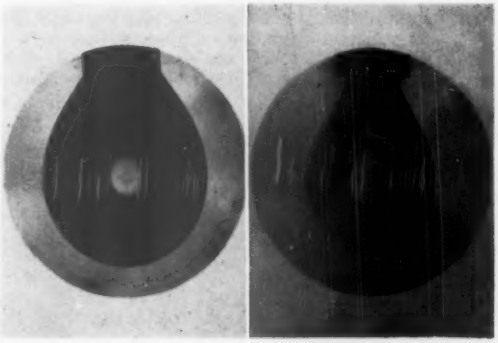

FIG. 7 — CHANGE IN WETTABILITY OF A SAMPLE OF AISI TYPE 316 STEEL.

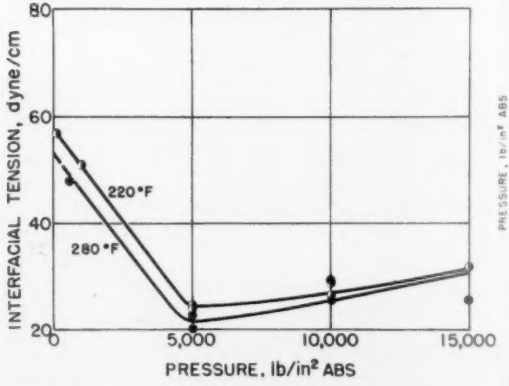

FIG. 5 — INTERFACIAL TENSION IN THE WATER-METHANE SYSTEM.

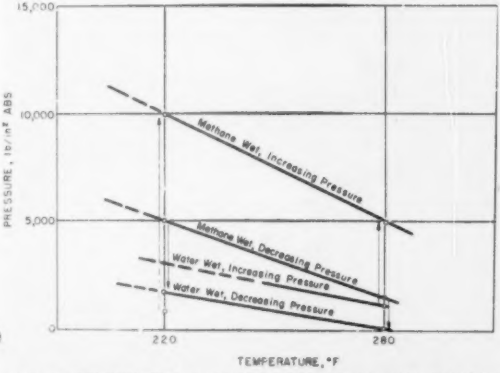

FIG. 8 — WETTABILITY OF A SAMPLE OF AISI TYPE 316 STEEL IN WATER-METHANE SYSTEM.

5,005 psi, and the temperature held nearly constant, this tip was wetted preferentially by methane as can be seen from Fig. 7B. For pressures between 1,005 psi and 5,005 psi, the wettability of the tip was uncertain. When a drop was placed on the tip between these pressures, it might wet part of the tip, or all of it or none of it. The pressures for the variation of wettability appear to be higher for a second sample of the same type of steel. For the second sample, boundaries of 2,000 psi for water-wet behavior and 10,000 psi for methane-wet behavior were established at 220°F, for increasing pressure.

Furthermore, hysteresis appears to be present. For the second sample, for decreasing pressure, the limits were about 5,000 and 2,000 psi, for methane-wet and water-wet behaviors, respectively. The behavior of the second sample is depicted in Fig. 8 at two temperatures. The authors suggest that the behavior of reservoir rock under these conditions might be worthy of investigation.

CONCLUSIONS

An apparatus has been built for the determination of interfacial tensions at reservoir pressures and temperatures and used for the methane-water system. The data show changes in interfacial tension in the 15 to 15,000 psi pressure range from 70 to 22 dynes/cm at 100°F and from 53 to 21 dynes/cm at 280°F. Data on the variation of wettability of stainless steel samples in water and methane have been obtained as a function of pressure and temperature. One sample was water-wet at 2,000 psi and methane-wet when the pressure was increased to 10,000 psi at 220°F. These limits were about 1,000 psi and 5,000 psi at 280°F.

ACKNOWLEDGMENT

The authors wish to express their appreciation to the Stanolind Oil and Gas Co. for permission to prepare and publish this paper.

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FIG. 9 — WORKING SECTION.

FIG. 10 — AIR BATH.

LOW TEMPERATURE DEHYDRATION OF NATURAL GAS

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ABSTRACT

A process for low-temperature dehydration of natural gas utilizing Joule-Thomson effect in expansion through a throttling orifice has been tested in a full-scale field installation. The results of these tests are presented in the form of performance curves from which the process may be easily evaluated.

The effect of separation temperature on condensate recovery from the process is also shown.

INTRODUCTION

The transportation of natural gas from producing well to the consumer has always encountered the problem of hydrate prevention. This problem has become increasingly important in the past ten years due to the rapid increase in produced gas volumes, production pressures, transportation pressures and distance from producing wells to consumer.

Natural gas, as normally produced from gas or gas-condensate wells, is saturated with water vapor at well-head conditions of temperature and pressure. The solution of the hydrate problem requires but one basic process — dehydration of the gas to a water content which will result in a water dew-point below the minimum temperature to be encountered from the producing well to the point of consumption.

Much of the recent development of gas and gas-condensate reserves in the Gulf Coast Area has been in locations which are accessible only by water. High well-head pressures, pipeline construction and maintenance costs and the desirability of final central gas-condensate separation facilities have stimulated the development of dehydration equipment which can be installed at each well and which will permit hydrate-free transportation of both gas and condensate in the same line to central facilities.

There are four types of natural gas dehydration processes now used:

1. Adsorptive processes.
2. Absorptive processes.
3. Chemical reaction processes.
4. Refrigeration processes.

The first three of these processes are indirect in that they require use of adsorbents, absorbents or reactive chemicals. These materials require regeneration and part of the total gas stream is consumed in the regenerative process. Indirect processes have a wide range of flexibility as defined by allowable operating pressure and temperature, but most are not easily adapted to automatic operation.

The refrigeration process described in this paper was designed for installation at the producing well-head. It requires no regenerative cycle and with normal well-head temperatures no external source of heat. The flexibility of this process is limited only by the pressure drop which may be allowed between well-head and transportation line.

THEORY

There are three basic physical concepts involved in the low temperature dehydration process. These are:

1. Formation of hydrocarbon hydrates.
2. Joule-Thompson effect resulting from the expansion of gaseous mixtures through a throttling orifice.
3. The equilibrium composition characteristics of water vapor and gaseous hydrocarbon mixtures.

The chemical composition and physical structure of hydrates have been described by several investigators.[2,4,6,7] Specific conditions of temperature, pressure and composition as well as the requirements for turbulence and presence of free water necessary for hydrate formation have been described by Katz.[6] Natural gas hydrates, as they are found in plugged gas pipe lines, have the appearance of packed snow. The mass of these hydrates has low continuous porosity and permeability.

Joule-Thomson effect, or the reduction in temperature which occurs when natural gas is throttled through a restrictive orifice, is the basic phenomenon which permits efficient use of refrigeration for the purpose of dehydrating natural gas. Joule-Thomson coefficients for gaseous mixtures of methane with ethane and with butane have been reported by Budenholzer, Sage and Lacey.[3] Brown[1] predicted temperature drops for pressure drops from enthalpy-entropy calculations. Aside from this work there were no fundamental data found which would be applicable to natural gas mixtures of varying spe-

[1]References given at end of paper.

Manuscript received in the office of the Petroleum Branch August 9, 1950. Paper presented at the Annual Fall Meeting of the Petroleum Branch in New Orleans, La., Oct. 4-6, 1950.

cific gravity. It was by assumption that the expansion of gas in equipment to be used in this process would be isenthalpic that the successful operation on the process was calculated.

The water vapor content of natural gas at saturation has been determined by several investigators.[6,7,9,11] All of these investigators show that the concentration of water in the vapor phase is reduced as a direct function of temperature and as an inverse function of pressure.

The low temperature dehydration process effects a degree of dehydration by:

1. Reducing the temperature of a water-saturated gaseous mixture by expansion through a restrictive orifice.
2. Reducing the equilibrium water content of the gaseous mixture as a direct function of temperature.
3. Forming and separating hydrate particles from the gaseous mixture by gravity difference.

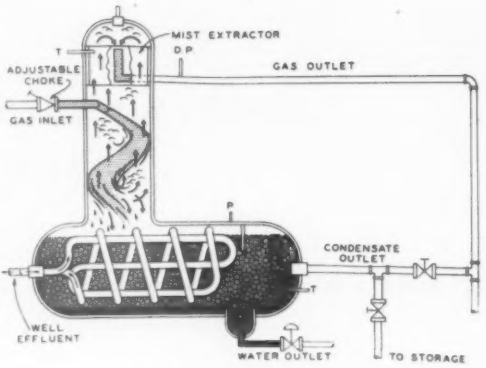

FIG. 1 — HYDRATE SEPARATOR.

TEST EQUIPMENT

The only equipment used in this test which was not of standard oil field type was the hydrate separator. This separator, shown in Fig. 1, was constructed with a vertical section 16 in. in diameter and 60 in. high, and a horizontal section 24 in. in diameter and 60 in. long. Gas entered this vessel after passing through an adjustable choke where the pressure was reduced throughout the test range. The temperature drop accompanying this pressure drop resulted in the condensation of a portion of the hydrocarbons and water vapor present and in the formation of hydrocarbon hydrates. The tangential flow of the entering mixture aided the separation of the hydrocarbon gases from the liquid hydrocarbons and hydrate particles.

The hydrocarbon gases passed upward through a mist extractor and into the gas outlet line. The liquid hydrocarbons and hydrate particles fell to the horizontal section where sufficient heat was added from the well effluent stream passing through a tube bundle to melt the hydrate particles. The condensed hydrocarbons and water from the hydrates were separated by gravity difference and withdrawn through separate outlets. The hydrocarbon liquids were either recombined with the dehydrated gas or run to storage and the water was removed to disposal.

Provision was made for temperature, pressure and dew-point measurement as shown in Fig. 2. Temperatures were measured by ASTM grade bulb-type thermometers, pressures were measured by bourdon-type gauges and dew-points by the Bureau of Mines Dew-Point Tester.

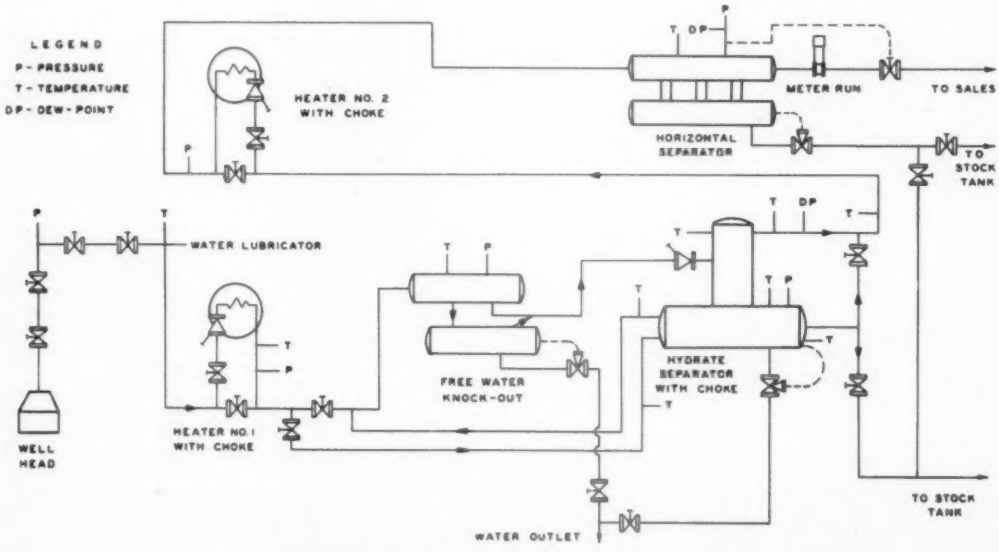

FIG. 2 — FLOW DIAGRAM — LOW TEMPERATURE DEHYDRATION UNIT.

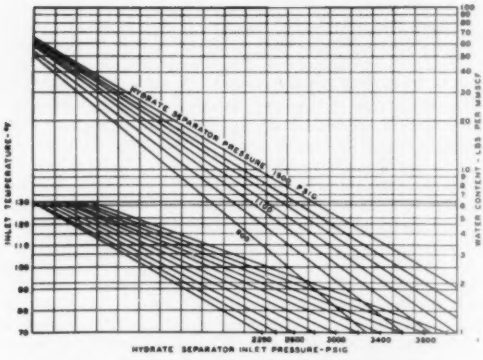

FIG. 3 — LOW TEMPERATURE DEHYDRATOR PERFORMANCE CURVES (BASED ON 0.64 SP GR GAS).

A schematic diagram of all equipment used in the test is shown in Fig. 2. This equipment was installed in such a manner that conditions of water content of the well effluent, producing well-head temperature and pressure, hydrate separator pressure, transportation line pressure drop and temperature could be simulated throughout a reasonable operating range.

The choke installed in Heater No. 1 was used to control the flowing well-head pressure. Heater No. 1 was used to control flowing temperature. The free water knock-out was used to remove excessive volumes of free water from the system.

The function of the hydrate separator has been described above.

Heater No. 2 and the choke at this heater were used to control simulated conditions of transportation line temperature and pressure drop.

The horizontal separator was used to separate the condensed hydrocarbons and gas which were recombined after discharge from the hydrate separator.

Hydrocarbon liquids were measured in a calibrated 25-bbl tank which had inlet connections at both top and bottom. The bottom inlet was flush with the inside of the tank shell. The top inlet was through a short nipple and 90° ell so that the condensate was diverted down and fell on the surface of the stock-tank liquid.

TEST PROCEDURE

Prior to each test run the well was opened to flow at a rate of approximately 10 MMcf/D to remove any volume of fluid which might have collected in the well bore. After the well had flowed for sufficient time to unload the fluid head, flow was reduced to the test rate of 1½ MMcf/D.

If the flowing temperature for a particular test was to be greater than that encountered from normal operation of the well, the well effluent was produced through Heater No. 1. To eliminate the possibility of undersaturation of the well effluent when heat input at Heater No. 1 was high, duplicate runs were made while injecting fresh water into the producing line. The water was injected at a constant rate and in sufficient volume to insure water-saturated vapor and liquid phases at the highest temperature in the system. None of these duplicate runs indicated discrepancy from previous data.

If the test pressure for a particular test was to be lower than that obtainable from normal well production, the choke upstream from Heater No. 1 was adjusted to provide the desired test pressure throughout the remainder of the system.

Flow rate was controlled by combined regulation of the choke at Heater No. 1, the choke at the hydrate separator and the choke at Heater No. 2.

The discharge pressure from the hydrate separator was controlled by dual regulation of the choke at the hydrate separator and at Heater No. 2.

Transportation line pressure drop and temperature were controlled by regulation of the line choke and Heater No. 2.

The pressure at the horizontal separator was controlled by sales line pressure and regulated by a pressure regulator on the discharge line from this separator.

With all conditions of pressures and temperatures regulated as described above, the system was allowed to operate for a period of six to eight hours, during which time temperatures, pressures, dew-point determination and volumes of gas and liquids removed from the system were recorded.

The variable conditions simulated throughout these tests were as follows:

Condition	Minimum	Maximum
Producing well-head pressure	2,200 to	3,750 psig
Flowing well-head temperature	70° to	130°F
Hydrate separator discharge pressure	900 to	1,500 psig
Transportation line pressure drop	0 to	600 psig
Transportation line temperature	40° to	90°F

Dew-point temperatures were converted to water content values from the data of McCarthy, Boyd, and Reid.[7]

RESULTS

The results obtained from these tests are shown in Figs. 3 to 9.

The many independent variables in this process preclude a precise presentation of all results in the form of direct data plots. The transposition and interpolation of observed data required for the construction of the performance curves involves a maximum deviation from observed data of less than 3 per cent with average deviation less than one-half of 1 per cent.

Fig. 3 summarizes the performance of this process throughout the test range. From Fig. 3 the water content of the gas from the hydrate separator can be determined for any condi-

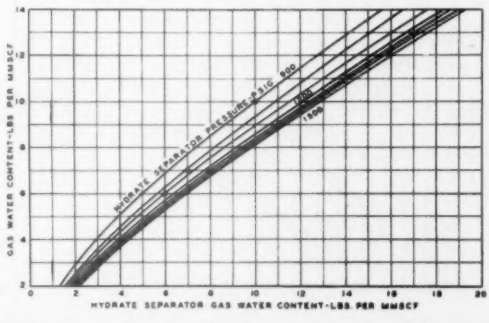

FIG. 4 — WATER CONTENT CHANGE OF DEHYDRATED GAS AFTER RECOMBINING WITH CONDENSATE.

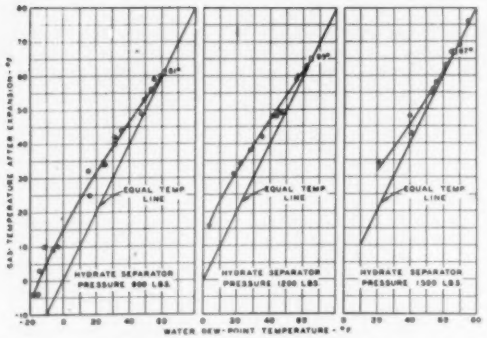
GAS TEMPERATURE AFTER EXPANSION - °F
WATER DEW-POINT TEMPERATURE - °F
EQUAL TEMP LINE
HYDRATE SEPARATOR PRESSURE 900 LBS
HYDRATE SEPARATOR PRESSURE 1200 LBS
HYDRATE SEPARATOR PRESSURE 1500 LBS

FIG. 5 — WATER DEW-POINT TEMPERATURE VERSUS HYDRATE SEPARATOR TEMPERATURE.

tions of inlet pressure and temperature and hydrate pressure. Use of these curves is described in a later section of this paper.

The change in water content of the dehydrated gas from the hydrate separator after recombination with condensate from this vessel is shown in Fig. 4. These curves are used in conjunction with Fig. 3 when the gas and condensate streams from the hydrate separator are to be recombined and again separated in a conventional gas-condensate separator. These curves show the magnitude of the partial resaturation of the under-saturated gas which exchanges water with a condensate upon recombination. This resaturation is not usually significant at conditions where the water content of the dehydrated gas is low and becomes progressively smaller as the water content increases until reversal takes place and the gas is further dehydrated. The points of reversal are shown for the various pressures by points on each pressure line in Fig. 4. Since resaturation is essentially a function of water solubility in the liquid phase and water vapor equilibrium in the vapor phase, it is significant that final separation pressure and temperature did not appreciably effect water content change.

A plot of the minimum gas temperature (temperature after expansion) versus water dew-point temperatures of the gas from the hydrate separator is shown in Fig. 5. From these curves it is evident that the dehydrating capacity of this process is not limited to the saturated water content at the lowest temperature in the system. Below the hydrate expectancy temperature (shown by the square points on Fig. 5) it was observed that the water dew-point temperature was lower than the lowest temperature observed in the system. It is probable that the lowest temperature in the system was at the vena contracta near the inlet nozzle, however, since the maximum temperature difference between the point of measurement in the hydrate separator and a point approximately 8 ft from this vessel in the gas outlet line was 2°F, it can be assumed that the lowest temperature in the system was not more than two or three degrees lower than that observed in the hydrate separator. Since the phenomenon of temperature/dew-point difference was observed only at temperatures below the hydrate expectancy temperature, or where hydrates were present, it is evidenced that natural gas hydrates have an adsorptive and/or absorptive capacity to remove water from the vapor phase.

Fig. 6 is a plot showing the temperature drop due to pressure drop observed in the hydrate separator. This plot is read by entering with initial pressure-temperature conditions and following the curved guide lines to final conditions of pressure and temperature. These curves show that the temperature drop per pound pressure drop is dependent on initial pressure and temperature.

While the primary purpose of these tests was to determine the dehydration capacity of the low temperature process, the condensate recovery data show that additional stock tank liquids can be recovered with low temperature gas-condensate separation.

The heat added to the condensed liquids in the hydrate separator and the cold area at the gas inlet resulted in a vaporization and refluxing action in this vessel. By this action light hydrocarbons were removed from the condensate and the remaining liquid was stabilized.

Fig. 7 is a plot of stock tank liquid recovered at various separation temperatures. These curves show the retrograde loss when pressures are increased from 900 to 1,500 lb, and the increase in stock tank liquid as separation temperatures are reduced.

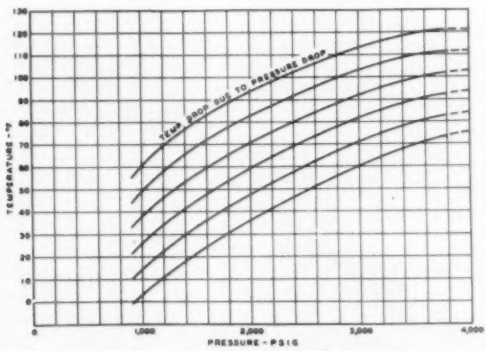

FIG. 6—NATURAL GAS EXPANSION—TEMPERATURE REDUCTION CURVE (BASED ON 0.64 SP GR GAS).

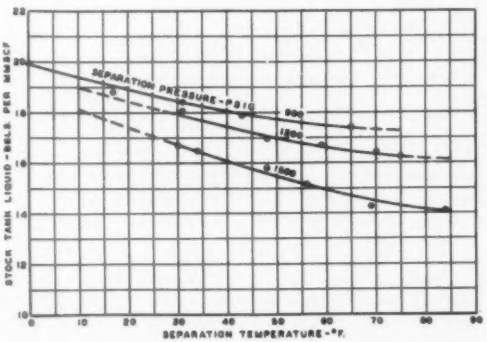

FIG. 7 — STOCK TANK RECOVERY (CONDENSATE INLET AT BOTTOM OF STOCK TANK).

Table I — Analysis of Well Effluent

Component	Mol %
CO_2	6.20
CH_4	92.80
C_2H_6	3.47
C_3H_8	1.16
IC_4H_{10}	0.39
NC_4H_{10}	0.35
IC_5H_{12}	0.14
NC_5H_{12}	0.11
C_6+	1.38
	100.00

Fig. 8 is a cross-plot of Fig. 7 showing stock tank liquid recovery versus separation pressure with parameters of temperature.

In Fig. 9 the effect of stock tank inlet location on stock tank recovery is shown. The fact that recoveries were lower when condensate was produced into the bottom inlet was due to the stripping action of the hydrocarbons vaporized by the pressure reduction between the separator and the stock tank. This action could be reduced by "staging" or incremental pressure reduction between separator and stock tank, with the vapors evolved at each stage removed before final entry into the stock tank.

CONCLUSIONS

Before drawing conclusions from the results presented above, it should be emphasized that one factor, the composition of the well effluent, was constant throughout these tests. An analysis of the hydrocarbons produced at the well-head is shown in Table I.

Based on relative thermodynamic property changes with change in natural gas gravity, the effect on dehydration results of composition difference, as normally experienced in natural gas and gas-condensate reservoirs, should not be great.

Specific conclusions drawn from the results of these tests are:

1. That natural gas can be dehydrated effectively at low temperatures resulting from expansion of the gas through a throttling orifice.
2. That the low temperature dehydration process is direct, continuous and limited only by available pressure drop through the process.
3. That water content change of dehydrated gas at pressures between 900 and 1,500 psig, when combined with water saturated condensate at the same pressure, primarily is a function of initial water content of the dehydrated gas and the pressure at which combination occurs.
4. That volumes of stock tank liquids recovered from low temperature and high pressure separation of gas and condensate are increased if these liquids enter near the top of the storage tank rather than at the bottom.

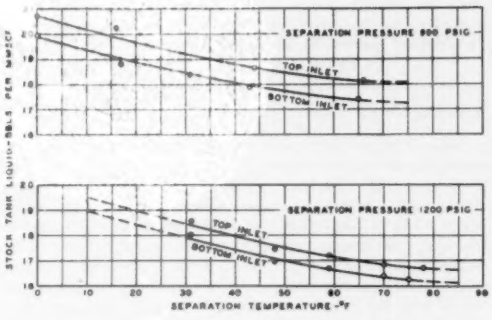

FIG. 9 — EFFECT OF STOCK TANK INLET LOCATION.

Additional Development of the Low Temperature Process

Since the tests described in this paper were completed, two significant changes have been made in the low temperature process. The first of these is the addition of a heat exchanger so that the cold gas from the hydrate separator is used to cool the well effluent before it enters the free water knockout. This heat exchange extends the operating range of this process by controlling the inlet temperature variable.

The second change in the process has been in the flow of the well effluent into the hydrate separator. By separating gas

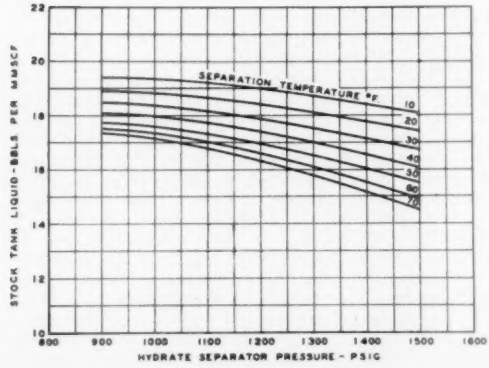

FIG. 8 — STOCK TANK RECOVERY (CONDENSATE INLET AT BOTTOM OF STOCK TANK).

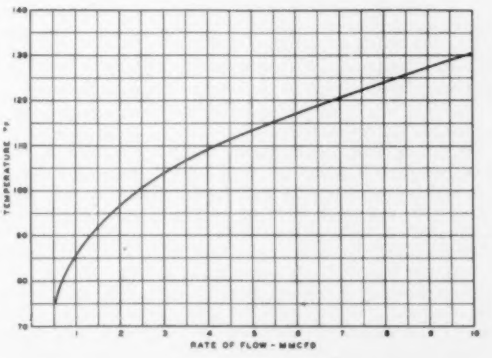

FIG. 10 — APPROXIMATE FLOWING WELLHEAD TEMPERATURES FOR GAS WELLS OF SOUTH LOUISIANA AREA.

from the liquid and expanding each through separate hydrate separator inlets, lower gas temperatures and consequently lower water content in the dehydrated gas is possible.

Use of Performance Curves

Fig. 3 is used to evaluate the performance of the low temperature process as follows:

Enter at the available hydrate separator inlet pressure (available wellhead pressure) on the bottom scale (range: 2,200 to 4,000 psig). Read along the diagonal guide lines to the point of intersection with inlet temperature line (horizontal lines range: 70 to 130°F). From this intersection read vertically to the intersection of the diagonal hydrate separator pressure lines (normally gas delivery line pressure). This last intersection is the water content to be expected and is read from the right-hand logarithmic scale. If the water content determined for a particular installation is above maximum specification, the feasibility of heat exchange between cold dehydrated gas and inlet stream can be investigated by fixing maximum allowable water content and available inlet pressure, then determining the temperature to which the inlet must be reduced.

If the dehydrated gas stream is to be recombined with condensate from the hydrate separator, final water content can be determined by Fig. 3 and Fig. 4. Water content of the gas from the hydrate separator is determined from Fig. 3, and this value is corrected directly by entering Fig. 4 with the hydrate separator gas water content and reading the corrected water content corresponding to the correct hydrate separator pressure.

In the preliminary stages of this work, it was noted that very little flowing well-head temperature data were available. A survey of 35 wells from 12 fields in the Gulf Coast Area was made; Fig. 10 is an average plot of the flowing temperatures measured. This curve is at best an approximation and should be used with the realization that wide deviations are probable, depending on many factors including producing depth, pressure, gas-oil ratio and volume of free water produced.

ACKNOWLEDGMENT

The authors express appreciation for the assistance of C. M. Netherland and J. E. Owens of the Sohio Petroleum Co., who performed the field tests, correlated data and contributed to the opinions presented herein.

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★ ★ ★

The Drift of Things

. . . as followed by **EDWARD H. ROBIE**
Secretary AIME

Foreign Policy

Though nothing is as important to personal, national, and world well-being as recent international, political and military developments, we have not lately made any comment on them. We have never been east of Cape Cod, west of the North Pacific coast, north of Saskatoon or south of Key West, so perhaps our point of view is too circumscribed to be worth presenting. However, an excellent guide book to Paris was written by a man who had never been to Paris.

What should the United States do? What should the United States have done? Plainly, those who ran the world before World War II did a sorry job of it. Those who have been running it since that war ended have done even worse, for here we are confronted with a strong possibility of an even more terrible era of devastation and bloodletting. But we have yet to hear any of the world's leaders apologize for their ineptitude. Any evidence of a contrite spirit seems to be missing. Worse still, the voting people seem complacent and not moved to demand a change.

Of recent public pronouncements by people in the public eye, that of our own Herbert Hoover on Dec. 20 over the Mutual Broadcasting System makes the most sense to us. At 76 Mr. Hoover spoke firmly and clearly and, of course, his background of experience in America, Europe and the Far East commands the highest respect. Two months before, he had opposed further military or economic aid to Europe until it set up a "united and sufficient" European army, and he urged reorganization of the United Nations without the Soviet Union and its satellites.

In his latest speech he expanded on his former statements. He first surveyed the global military situation, pointing out that the Communists in Europe and Asia have over 300 trained and equipped combat divisions, with more than 30,000 tanks and 10,000 tactical planes, though their long-range air power is limited and their sea power confined to submarines. Some day, he said, "the Communistic empire will go to pieces. But in the meantime they are cannon fodder." Facing the Communists in the Far East are the already defeated Koreans, and perhaps twelve combat divisions in addition. Among our friends, only Formosa and Turkey, in Asia, have any important military strength. Among the European continental countries, Mr. Hoover estimates something less than 20 combat divisions, with disunity and a feeble will to defend themselves. The British commonwealth has perhaps 30 combat divisions, with a good air force and a superior navy. Here in the U. S. we are planning 30 combat divisions with a gigantic air force and navy.

With the above situation, Mr. Hoover can see no hope of defending Asia or continental Europe against the Communist horde by land forces, should the Communists decide to attack, even though the non-Communist countries had the will and means to defend themselves, which they do not have. For the U. S. to undertake to fight the Communist countries in Asia and continental Europe practically single-handed is sheer folly. That would be the graveyard of millions of American boys and would end in the exhaustion of this Gibraltar of Western civilization. Even were Western Europe armed far beyond any contemplated program, we could never reach Moscow. The Germans failed with a magnificent army of 240 combat divisions and with powerful air and tank forces, as contrasted with the sixty divisions now being talked about."

So Mr. Hoover proposes that we defend Western civilization by arming our air and naval forces to the teeth, rather than send a land army in a futile mission to continental Europe or Asia. Our eastern frontier would be in Britain; our western on Japan, Formosa and the Philippines, provided they were willing to try to defend themselves with our help. Presumably we would see that Communist aggression was stopped everywhere in the Americas.

Mr. Hoover has been accused of preaching isolationism, but surely the frontiers indicated are sufficiently broad to emphasize our desire to assist other countries as far as we are able. He has also been accused of being a defeatist. On the contrary, he offers a realistic program that has much more hope of success than does a more extended policy of spreading our military and economic policy so thinly that defeat would be practically certain, with the probable downfall of our economic system and possibly even of our form of government. He has been accused of scuttling the Atlantic Charter and the North Atlantic Treaty, but we see nothing in those agreements that commits the United States to undertake the defense of Europe on a scale far greater than the European countries themselves are willing to assume, which, as Hoover states, so far is practically nil.

The United States, in other words, cannot be the omnipresent policeman throughout the troubled non-Communist world. That, thinks Hoover, is the job of the United Nations. The United States should not have had to provide 90 per cent of the military force in Korea. Other United Nations countries could at least have provided men, if not munitions. If they are unwilling to assume their proper share of the burden, the United States must be realistic and pull in its lines a bit. Hoover suggests four things for the United Nations to do: (1) Declare Communist China an aggressor; (2) Refuse admission of this aggressor to its membership; (3) Demand that each UN member country cease furnishing or transporting supplies of any kind to Communist China that can aid in its military operations; (4) Pass a resolution condemning the infamous lies about the United States.

We think it is about time that the countries opposed to Russia's policies get together and make the United Nations work. There is still a good chance for this organization to be effective if the Russian shackle on its activities is removed. A UN army, navy and air corps that will be able to stand off Russia is needed, to which every member nation should contribute. It should operate under codified international law, defining, among other things, what is meant by aggression. No nation should have the right to veto any action that it might consider to be to its disadvantage, and yet this veto power was one of the things that the United States originally insisted on having included in the UN Charter.

The United States should, we might add, temper its crusade for the institution of our brand of democracy and freedom throughout the world. It works to our general satisfaction, but it probably would not function satisfactorily in many other countries — Latin America, for example. It is right that we are aiding even Communist Yugoslavia. If a country minds its own business and does not molest its neighbors, its form of government should be its own affair.

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Discussion Due On Liberalized Policy

Liberalization last summer of the Institute's policy on controversial matters opened the door to the Board's expressing its views "on matters pertaining to the mineral industries that are of vital interest to the nation in times of danger."

Few will dispute the fact that we are now facing perils that are a serious threat to the American way of life. To what extent, and how, can the Institute help in meeting the demands made on the mineral industry by the present emergency?

At the luncheon of the Mineral Economics Division, Feb. 20, at the Annual Meeting in St. Louis, Institute officials will present their interpretation of the revised resolution (adopted June 22, 1950; see August, 1950, issue of the JOURNAL OF PETROLEUM TECHNOLOGY) and comment on methods of taking such action as is permitted under present policies. There will be ample opportunity for discussion from the floor. ★

McLaughlin and Robie Visit Branch Sections

AIME President D. H. McLaughlin visited several Petroleum Branch sections from November 22 to 26 in a tour that was heartily welcomed by Petroleum Branch members. On November 22, accompanied by Branch Secretary Joe B. Alford and PETROLEUM TECHNOLOGY Editor Jess E. Adkins, he visited the East Texas Section in Kilgore. He briefly discussed AIME progress and affairs, and spoke on the function of gold in our national economy. A review of his address appeared on Section 1, page 19 of the January, 1951, PETROLEUM TECHNOLOGY.

After arriving in Houston on November 23, President McLaughlin attended a luncheon in his honor given by Harold Decker, an AIME director, and officers and directors of the Gulf Coast Local Section. A meeting of the section for McLaughlin was held in the Houston Club that evening.

Herbert E. Treichler, Sr., vice-president and general manager of the Texas Gulf Sulphur Co., took the president to Newgulf, Tex., for the night of November 23, where he was shown company operations the next day. A company plane then flew McLaughlin and Alford to Corpus Christi for a meeting of the Southwest Texas Local Section on the evening of November 24.

From Corpus Christi, McLaughlin flew to Midland for a meeting of the Permian Basin Section on November 25, and in returning to San Francisco, he visited the Arizona Section on November 27.

Another appreciated visitor to the Petroleum Branch area was Edward H. Robie, AIME secretary, during the period of January 9 to 18. Accompanied by Branch Secretary Alford, he visited petroleum local sections as follows: Delta Section, January 9; Mississippi Sub Section, January 10; Gulf Coast Section, January 11; San Antonio-Austin sub section, January 12; North Texas Section, January 15; Mid Continent Section, January 16; Kansas Section, January 17; and Oklahoma City Section, January 18. Robie discussed AIME affairs of interest to members, and Alford presented a financial report for the Petroleum Branch in 1950. ★ ★ ★

Kansas U. to Sponsor Natural Gas Lectures

The Department of Petroleum Engineering at the University of Kansas has announced that a series of lectures on Natural Gas Engineering will be given by Donald L. Katz March 26-27, 1951. The lectures are to be given on the campus of the university at Lawrence, Kans., and all engineers and operating personnel interested in the field of Natural Gas Engineering are invited to attend.

These lectures have been planned as a refresher course and to present new ideas and methods of value to engineering personnel. The program has been arranged so as to give maximum benefit to people concerned with production and transportation of natural gas in the Mid-Continent area; all methods and ideas presented will be directly applicable to gas engineering problems in that area.

The lectures will cover four main topics, and each will be allowed one-half day for discussion. The main topics to be discussed are: (1) Physical and Thermodynamic Properties of Natural Gas; (2) Flow of Natural Gas in Pipes; (3) Flow of Gas in Reservoirs; and (4) Prediction of Gas Reserves. ★

Meetings of Interest

The following meetings will be held April 23-26 in St. Louis, Mo., at the Jefferson Hotel:

36th Annual Meeting, American Association of Petroleum Geologists.

24th Annual Meeting, Society of Economic Paleontologists and Mineralogists.

20th Annual Meeting, Society of Exploration Geophysicists.

Proposed for Membership, Petroleum Branch

Total AIME membership on December 31, 1950, was 17,082; in addition, 4,534 Student Associates were enrolled.

ADMISSIONS COMMITTEE

A. J. Phillips, Chairman; George B. Carless, John T. Sherman, Lloyd C. Gibson, R. D. Mallison, Plato Malozemoff, Ivan Given. Alternates, H. P. Croft, F. W. Hanson, T. D. Jones, Frank A. Ayer, H. W. Hitzrot, H. K. Masters.

Institute members are urged to review this list as soon as the issue is received and immediately to wire the Secretary's office, night message collect, if objection is offered to the admission of any applicant. Details of the objection should follow by air mail. The Institute desires to extend its privileges but does not desire to admit persons unless they are qualified.

In the following list C/S means change of status; R, reinstatement; M, member; J, Junior Member; AM, Associate Member; S, Student Associate; F, Junior Foreign Affiliate.

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Long Beach — Mulker, Fred R. (J) (C/S-S-J).
Los Angeles — Dunham, Clifford W. (J) (C/S-S-J); Laurie, Archibald McK. (J) (C/S-S-J); Loy, Milton E. (M) (C/S-J-M).
Newhall — Graybeal, Orán A. (M) (C/S-J-M).
Pasadena — McCloskey, Downs, Jr. (J).
San Pedro — Holland, Kenneth M. (J) (C/S-S-J).

COLORADO

Denver — Gregg, Dennis E. (J) (C/S-S-J); Grimm, Paul E. (J).
Pueblo — Elton, Frederick W. (J) (C/S-S-J).

ILLINOIS

Centralia — Chapman, Peter F. (J).

KANSAS

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Topeka — Birtell, James C. (J) (C/S-S-J).
Wichita — Goin, Charles M. (J) (C/S-S-J).

LOUISIANA

Harvey—Meltzer, Bernard D. (J) (C/S-S-J).

MARYLAND

Silver Spring — Lebsack, Milton J. (M) (C/S-J-M).

MICHIGAN

Grayling — Baldwin, Elwood L. (J) (C/S-S-J).
Mt. Pleasant — Austin, Merton E. (M).
Roscommon—Crate, James A. (J) (C/S-S-J).

MISSOURI

Springfield — Haymes, William G. (J) (C/S-S-J).

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Maljamar — Iverson, Barley G. (J) (C/S-S-J).

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Healdton — Simms, Byron O., Jr. (J) (C/S-S-J).
Lawton — Graham, William B. (M).
Norman — Roberts, Sanford M. (J) (C/S-S-J).
Oklahoma City — Morgan, Neil R. (J) (C/S-S-J); Rennie, Preston G. (J) (C/S-S-J).
Ponca City — Brown, Chester L. (J) (C/S-S-J).
Shidler — Gray, Robert (J) (C/S-S-J).
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Borger — Holcomb, James A. (J) (C/S-S-J).
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Fort Worth — Cummins, Ralph H. (M); Keener, M. Herbert L. (J) (R,C/S-S-J).
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Tyler — Kidd, J. Pat (J) (C/S-S-J).
Van — Schrenkel, Jack (J) (C/S-S-J).
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Calgary — Young, James W. (M).

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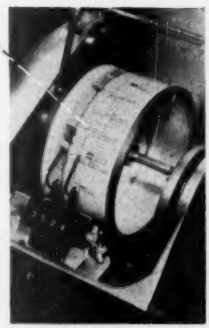

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Budget Reviewed By Finance Committee

At their meeting on Dec. 20, 1950, the Executive and Finance Committees reviewed the preliminary budget of the Institute for the coming year, which had previously been prepared by the Finance Committee. It was pointed out that the most difficult item to estimate at this time is advertising income, because 1951 contracts will not be in hand before February. However, indications were that advertising income could be placed at $131,500, compared with an expected $104,000 in 1950. MINING ENGINEERING is expected to yield $63,000, the JOURNAL OF METALS $45,000, and the JOURNAL OF PETROLEUM TECHNOLOGY $23,500. Total income in this preliminary budget is $496,000, and total expenses approximately $482,000. A final budget will be presented later.

One increased item in the expenses of the Institute in 1951 will be incurred by inclusion of AIME employees in Social Security, as permitted under the new law. They will also be included in the provisions of the New York Disability Benefit law, to provide compensation for disabilities incurred off the job. As employes suffer a deduction from salaries for these benefits, the directors voted to assume the burden of hospitalization insurance on an individual basis for all employees. Heretofore most of them had been covered, but entirely at their own expense.

Some curtailment of AIME income is likely to result from another action of the directors at this meeting: it was voted that no more orders should be accepted for shipment of AIME publications to the USSR, Poland, Czechoslovakia, or Romania. Heretofore, close to 300 annual subscriptions for Institute journals have been booked for shipment to these countries, to say nothing of numerous bound volumes. ★ ★ ★

Engineering Library Revises Photo Service

To facilitate the location of engineering and technical material, the Engineering Societies Library recently revised its photoprint service, Ralph H. Phelps, director, has announced.

Photoprint copies of material in the library can be supplied as negative prints, white on black, for 40 cents a print, with a minimum charge of $1. Any two facing pages which together measure 11 x 14 inches or less can be taken on one print. Larger material will require one print per page.

Material not in the library will be supplied at the same rate, plus a $3 service fee for locating the article, if it can be found in this country. There is no service charge if a requested search is not successful.

Requests for the searching service may be for individual orders, or as a blanket authorization covering all orders for a specified period of time.

Orders and requests for the searching service should be sent to Engineering Societies Library, 29 West 39th Street, New York 18, N. Y.

Members of the AIME, ASCE, ASME, and AIEE are entitled to a 20 per cent discount on the service fee and a reduction of 5 cents on each photoprint, if the material is ordered for their personal use. ★ ★ ★

Gulf Coast Section

Continued from Page 19, Section 1

1949. His paper has also been published in November, 1950, issue of the JOURNAL OF PETROLEUM TECHNOLOGY. He discussed the field, its separate reservoirs, their performance histories, the injection program, some of its problems and accompanied his talk by statistics on the field.

A short color-sound movie on the subject, "Miscroscopic Studies of Fluid Flow through Capillary Tubes," was shown through the courtesy of the South Penn Oil Co. and Pennsylvania State College. ★ ★ ★

Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 601 Continental Bldg., Dallas 1. Show return address on envelope. These replies will be forwarded unopened and no fees are involved.

Replies to the positions coded Y4735, Y4658(a), Y4658(b) and Y4642 below should be addressed to: Engineering Societies Personnel Service, 8 West 40th St., New York 18, N.Y. The ESPS, on whose behalf these notices are published here, collects a fee from applicants actually placed.

PERSONNEL

♦ February graduate, 26, married, wishes position related to geology. Has MS in geology and is available immediately for employment. Salary required, $325. A veteran of World War II and a Lieutenant (jg) in USNR. Code 142.

POSITIONS

♦ Engineers. (a) Petroleum Engineer Trainee (CNY-1279-W), 21-24, B.S. in petroleum or mechanical engineering. No experience required, but summer work in oil fields preferred. Will perform general field and office petroleum engineering work including bottomhole pressures, checking well depths, performing routine analysis work in the laboratory, checking and posting pool maps, gas oil ratios, etc. Single status. Salary, $5,700 a year. (b) Petroleum Engineer Trainee (CNY-1280-W), 21-24, B.S. in petroleum engineering, preferably with some experience in petroleum industry. Will be required to learn Spanish. Will be trained to obtain a general knowledge of the industry, and obtain a good idea of a petroleum or chemical engineer's job. Salary if single, $5,700 a year; if married, $6,600 a year. Single status for six months. Location, Venezuela. Y4735.

♦ Instrumentation engineer, graduate chemical, with a minimum of eight to ten years' experience in chemical or oil refinery work. Must know electric and pneumatic instrumentation. Salary, $6,000-$7,200 a year. Y4658(a).

♦ Buyer with experience in purchasing materials for the chemical industry from large petroleum refiners. Salary, $4,800-$6,500 a year. Location, New York, N. Y. Y4658(b).

♦ Engineers. (a) Chief Reservoir Engineer, 25-40, with degree in engineering and about five to eight years' experience in petroleum engineering. Location, Peru. (b) Senior Petroleum Engineer, 25-40, with degree in petroleum engineering or equivalent, and about four to eight years' experience in reservoir engineering. Location, Peru. (c) Petroleum Engineering Laboratory Analyst, 25-40, with an engineering degree. Location, Colombia. Wellsite Mud Engineer, 25-35, with three to five years' experience. Location, Colombia. Y4642.

♦ Petroleum reservoir engineer with four years' experience to work on Tulsa engineering staff large independent. Supply usual application data including salary. Replies will be confidential. P.O. Box 2039, Tulsa.

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San Joaquin Valley

Continued from Page 24, Section 1

32S, 32-5G, and 68-31S. The best repressuring results have been obtained on the north and northeast where restraining edgewater helps to make the gas expansion more gradual and uniform.

Under the Remedial Program, water entry has been excluded in about 70 wells. Also, under this program, 41 wells have been abandoned in the old Hay-Carman area where deteriorated casing constituted a hazard to the reservoir and to personnel.

A water encroachment study was made following the war in a fault block on the north flank. The purpose of the study was to determine the effect of allowing the edgewater to encroach up-structure or, in other words, to ascertain the feasibility of producing the field by water drive. The down-structure wet wells were shut in and the water allowed to advance up-structure during 1946 and 1947. The water was observed to channel preferentially up the base of the SS-1 sand, leaving behind quantities of oil downstructure. This is thought to be owing mainly to the relatively high permeability variation. Recovery by water drive in the Shallow Zone is to be avoided. Since 1948 in this fault block water has been produced down-structure at maximum rates and at the same time dewatering up-structure. The dewatering has improved the productive capacity of the fault block but production is still below the 1945 level before the water was allowed to encroach up-structure.

Another study was made to evaluate the feasibility of production by gravity drainage. The east end of the field, where most of the wells are completed in the SS-1 sand, was selected for this study. The idea was to produce maximum quantities of water down-structure so as to create a pressure sink to which oil might gravitate and be produced. Gravity drainage, however, was not attainable since the edgewater came in as rapidly as produced and sand trouble precluded increasing the producing rates any further.

Plans are being made for the completion of the gas gathering facilities together with the construction of a new gasoline plant. The lines yet to be installed are mainly vacuum, low pressure, and gas injection lines. The plant is being designed for an initial rate of 50 MMcf/D and will be located in the central part of Elk Hills. The old plant on Section 3G will be used mainly as a booster station. It is expected that installation of the gas gathering and plant facilities will begin sometime next summer. In regard to oil gathering lines, the main lines are in. Storage and shipping facilities are located at the Buena Vista Tank Farm, 25S and 23S.

Current oil production averages about 5,100 B/D from the Shallow Zone and 1,800 B/D from the Stevens Zone. Since the end of the Primary Period last August, Navy takes 8/9ths of the Shallow Zone production and Standard 1/9th. Stevens production is always divided on the basis of Stevens Zone participating percentages which are approximately 4/5th Navy and 1/5th Standard. Navy's share of the oil production since last July has been shipped to the coast and thence to Japan for use in the refineries there under a program administered by the Army. Shallow Zone Special oil, which is virtually wax free, averages about 20 gravity; Shallow Zone light oil averages about 27 gravity. Stevens Zone oil runs about 36 gravity. ★ ★ ★

Pacific Junior Group

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the oil to flow into pits. The oil so collected is then pumped in stages to the surface where it is refined and shipped. The operation requires 1,400 men and is extremely costly, particularly due to the excessive amount of sand and other foreign material which must be cleaned from the oil.

From Northern Germany, Huntsinger travelled south to the great industrial area of the Ruhr. He described the Ruhr as the most concentrated area of heavy industry in the world. Compared to the Ruhr, Pittsburgh or the Ohio Valley are like an olive in the center of a pie.

Huntsinger toured the Mannesman Tube Mill while in the Ruhr. He described their mills as the ultimate for tubular goods fabrication. They are laid out in long narrow bays and the metal is processed through the various stages in a straight line. Cat walks are provided above the production line so that one can walk along and view each stage of the operation. It was in this plant that Huntsinger noted the newest and most modern of the mills being torn out by British occupation authorities under the dismantling program. Querying plant management on their seeming lack of concern, he was advised that they had already laid out an even more modern and improved mill to be constructed with ECA funds as soon as the British dismantling was completed.

Continued on Page 7, Section 2

Meetings of Interest

The 1951 Spring Meeting of the Southwestern District, American Petroleum Institute, will be held March 7-9, in the Hotel Beaumont, Beaumont, Tex. Reservations should be addressed to Howard Hicks, chairman, API Hotel Reservations Committee, c/o Chamber of Commerce, Beaumont, Tex.

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Personals

FRED E. SIMMONS, JR., has opened a consulting office for petroleum engineering and geology in the Hibernia Bank Building in New Orleans, La. He was formerly head of the petroleum engineering department of the Louisiana Land and Exploration Co. As consultant, he will specialize in subsurface geology, property appraisal and property management.

+

WALTER R. BERGER and CHAS. H. PISHNY have formed a partnership under the firm name of Berger and Pishny to do consulting work in geologic interpretations and valuation of oil and gas properties. Their offices are at 901 Commercial Standard Building, Fort Worth, Tex.

+

JOHN D. GILL has retired as economist and director of The Atlantic Refining Co. after being associated with the firm since 1912. His first position with Atlantic was as lubrication research engineer in the Laboratory Department and in 1928 he was appointed head of the Economics Department. He was elected to the board of directors in 1931.

+

RICHARD C. HARRIS has been appointed resident manager of The Atlantic Refining Co.'s operations in Venezuela. He will be stationed in Caracas. He first became associated with the company in 1938 as resident geologist in Havana, Cuba. In 1941, he was named chief geologist and was transferred to headquarters in Philadelphia, Pa.

+

JACKSON M. BARTON is now manager of the geological department, Deep Rock Oil Corp., Tulsa, Okla.

GLEN W. BARB, petroleum engineer for the Magnolia Petroleum Co., was transferred to the Vanderbilt District, Edna, Tex. He was formerly located at Morgan City, La.

+

PAUL S. JOHNSTON is now connected with the Texas Pacific Coal & Oil Co., Hobbs, N. Mex., as district superintendent.

+

BURRELL G. TAYLOR, junior petroleum engineer with the Kerr-McGee Oil Ind. Inc., was recently transferred from Sunray, Tex., to Oklahoma City, Okla.

+

AARON FRANK GIEBEL is petroleum engineer trainee for the Herman and G. R. Brown Oil Co., Snyder, Tex.

+

BRANDON H. GROVE has been transferred from the New York office to Cairo by the Socony Vacuum Oil Co., Inc.

+

DOUGLAS D. HOWARD, district geologist, has been transferred from the Jusepin District, Monagas, Venezuela, to the Lagunillas District, Zulia, Venezuela, by the Creole Petroleum Corp.

+

PAUL F. BARNHART, formerly associated with Frank and Geo. Frankel, oil producers, has opened offices as an independent oil operator and petroleum engineer at 1228 Commerce Building, Houston, Tex. He was with the former firm for eight years prior to opening the present offices. For the past 15 years, he has been active in supervision of acquiring, drilling and production operations of properties developed in Texas, Arkansas, Mississippi, Louisiana and Oklahoma.

WILLARD HASSEBROEK has been made technical supervisor of Hydrafrac Service Operations of Halliburton Oil Well Cementing Co. He has been with the firm for the past 16 years working throughout the Mid-Continent area as field engineer and since 1942 has been at Duncan, Okla., home offices of Halliburton.

+

RAYMOND H. EUBANK has joined the Sun Oil Co., Kilgore, Tex., as petroleum engineer trainee.

+

KENNETH E. MEYER has joined the Petroleum Advisers, Inc., New York, N. Y., as petroleum engineer.

+

ROBERT S. MOEHLMAN will continue as consulting geologist for the Kelowna Exploration Co., Ltd., but will be located at the Austral Oil Exploration Co., Inc., Houston, Tex., as vice-president. He is also associated with William A. M. Burden Co.

+

HERBERT L. PEEL is now working as petroleum engineer for the Vickers Petroleum Co., Inc., Lindsay, Okla.

+

JAMES K. STANLEY is now associated with the Standard Oil Co. of Indiana, engineering research dept., Chicago, Ill. He was formerly connected with the Westinghouse Electric Corp. research laboratories, E. Pittsburgh, Pa.

+

L. B. FORNEY is now geologist for the Sohio Petroleum Co., Lafayette, Ind.

Air Force Offers Vacancies for Engineers

There now exists a limited number of vacancies in United States Air Force Headquarters at the Pentagon for Mining and Metallurgical Engineers who also possess Photo Interpretation experience or potential, in the following jobs with grades and salaries listed:

Photo Intelligence Specialists GS-9 ($4,600 per annum, starting salary) through GS-12 ($6,400 per annum, starting salary).

Civil Service grades assigned will depend largely on education and/or equivalent experience in the field of mining engineering and/or metallurgical engineering. Photo interpretation experience is desirable but not absolutely required. Every effort will be made to place qualified applicants in positions commensurate with their education and experience. Inquiries regarding these positions and requests for the required Civil Service application forms should be made to the address below: Photo Intelligence Section, Reconnaissance Branch, Directorate of Intelligence, Headquarters, United States Air Force, Washington 25, D. C. ★ ★ ★

Pacific Junior Group

Continued from Page 5, Section 2

At Mullheim on the Ruhr River, Huntsinger visited the plant of Haniel & Lueg, one of the largest European suppliers of oil field equipment. This plant, prior to the war employed some 3,800 employees, but during Huntsinger's visit, there were but 120 persons employed. Their work week is six days on a ten hour a day shift. The practice is encouraged by their strong union organizations in what Huntsinger described as a unified effort to produce cheaper and more efficiently in an effort to regain independence.

One of the newer developments in the plant was a revolutionary torque converter which the management refused to discuss, due to the previously mentioned fact that the United States does not honor German patents. Huntsinger later saw this converter in operation with one diesel engine powering a drilling rig near Hanover. He described it as an apparently perfect power transmission medium with no observable whine or speeding up with changes in loads.

Huntsinger was also impressed with the rapid strides being made with inspection equipment for tubular goods and steel. He described equipment which can give spot check hardness readings on drill collars coming out of the hole to .240 in. in depth in eight seconds. He observed one inspection of a hollow turbine shaft 10 in. in diameter with 3-in. walls where a flaw was precisely located and later proved by cutting through the shaft. In general their inspection instruments are ten years ahead of ours, due to the fact that they were able to start from scratch after the war and build new equipment without amortizing the old.

Huntsinger described one plant where he was particularly impressed by the brand new American machine tools with which it was completely equipped. Discussion with plant management brought out the fact that the plant was in an area which had alternated between British and American control. While under British control, the equipment had been removed and, for lack of better disposition, stored in a large shed on the premises. After return to American control the plant was put back into operation but with completely new equipment financed by ECA, due to British control over the old tools which Huntsinger observed still stored in the shed. ★ ★ ★

Book Donations Needed For Louvain Library

While the famous chimes given to the library of the University of Louvain, Belgium, by a group of American engineering societies after World War I, survived the fire and bombing of World War II, the books in the library were destroyed. The building has been restored, shelves have been replaced, and some books have been collected. But few recent books in English fill those empty shelves.

A plea has been made to American engineers to help in this matter. The CARE UNESCO Book Fund will channel any donations for books to Louvain; and a bookplate enscribed with the name of the company or organization will be inserted on all gifts of $10 or more. While Belgium and Europe were in a long war, resulting in an intellectual blackout, American research and progress continued. Recovery in this area can be speeded by making American knowledge available through subscription to Louvain through the CARE UNESCO Book Fund. ★ ★ ★

Meetings of Interest

The Missouri School of Mines and Metallurgy will present a symposium on water flooding on the campus in Rolla, Mo., Feb. 23. Hotel reservations may be arranged on request to the Mining Department of the school.

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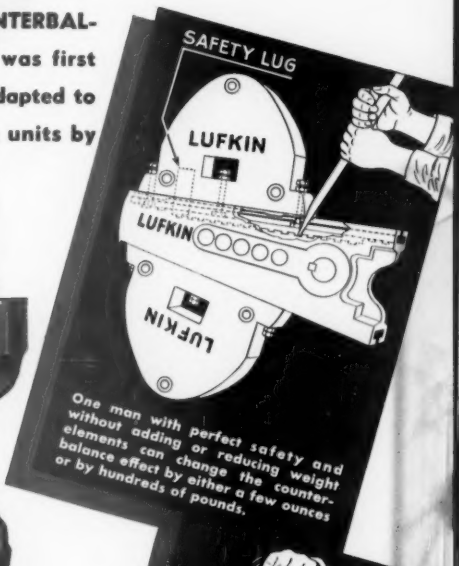

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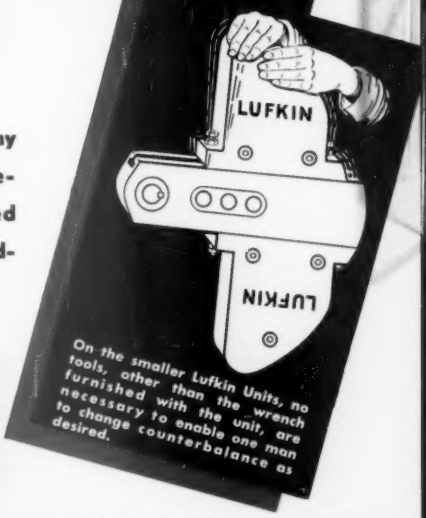

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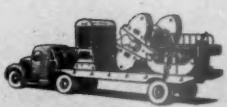

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